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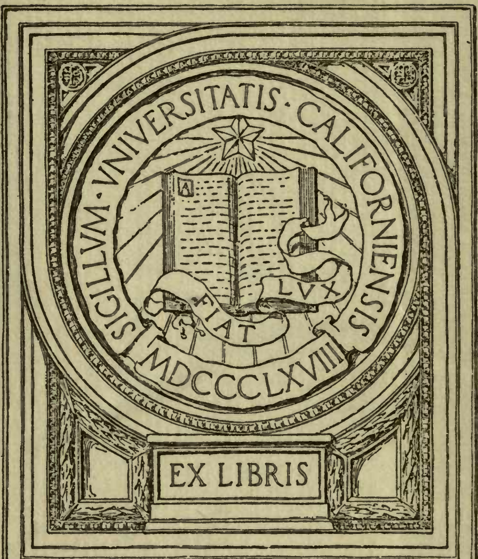

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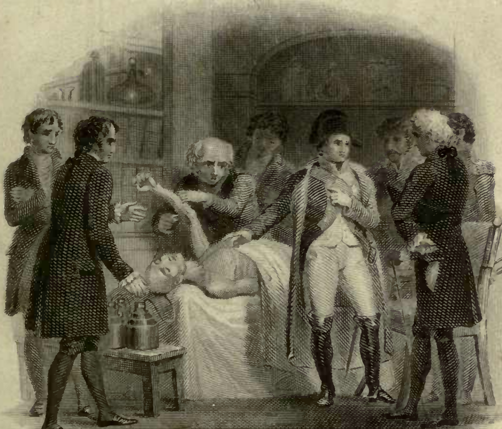
A MANUAL
of
ELECTRICITY, MAGNETISM,
and
METEOROLOGY,

by
Dionysius Lardner, D.C.L. F.R.S. &c. &c.

IN TWO VOLUMES.

Vol. I.



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A MANUAL OF ELECTRICITY, MAGNETISM, AND METEOROLOGY.

INTRODUCTION.

HISTORICAL NOTICE OF ELECTRICAL DISCOVERY.

I. ELECTRO-STATICS.

(1.) Although it has been reserved for modern times to bring to perfection the methods of investigation pursued in physical researches, these great divisions of human knowledge have nevertheless been always progressive. If the labours of the ancients were obstructed, their advancement retarded, and their productions disfigured by fantastical theories; the facts they accumulated, the phenomena they described, and the observations they recorded, have formed a bequest of the highest value to the better disciplined inquirers and observers of later days. Astronomy, the mechanics of solid and fluid bodies, and the physics of the imponderable agents, light and heat, received severally more or less atten tion at an early epoch of the progress of human knowledge; and the results of ancient researches in some of these branches of science, astronomy for example, form an important element of the knowledge we now possess. Electricity, however, is a remarkable exception to this state of progressive movement. To that particular division of physics antiquity has contributed absolutely nothing. The vast discoveries which have accumulated respecting this extraordinary agent, by which its connection with and influence upon the whole material universe, its relations to the phenomena of organized bodies, the part it plays in the functions of animal and vegetable vitality, its subservience to the uses of man as a mechanical power, its intimate connection with the chemical constitution of material substances, in fine, its application in almost every division of the sciences, and every department of the arts, have been severally demonstrated, are exclusively and peculiarly due to the spirit of modern research, and in a great degree to the labours of the present age.

(2.) The beginnings of science have often the appearance of chance. A felicitous accident throws a certain natural fact under the notice of an inquiring and philosophic mind. Attention is awakened and investigation provoked. Similar phenomena under varied circumstances are eagerly sought for; and if in the natural course of events they do not present themselves, circumstances are designedly arranged so as to bring about their production. The seeds of science are thus sown, and soon begin to germinate. Whether such primary facts are really fortuitous, or ought not rather to be viewed as the prompting of HIM, whose will is that intellectual progression shall be incessant, it is certain that they not only give the first impetus to science, but their occasional and timely occurrence in its progress produces frequently greater effects on the celerity of its advancement than the most exalted powers of the human mind, unsupported by such aid, have ever accomplished. It may then be imagined that if any such hints were offered by ordinary phenomena, an agent so all-pervading as electricity could scarcely have eluded notice, or failed to command attention, during a succession of ages which witnessed the growth and extension of so many other parts of natural knowledge. On the contrary, the class of effects in which electricity originated was observed by and well known to the early philosophers of Greece. THALES, six centuries before the Christian era, was acquainted with the property of amber, from which electricity derives its name*; and Theophrastus and Pliny, as well as other writers, Greek and Roman, mention the property of this and certain other substances, in virtue of which, when submitted to friction, they acquire the power to attract straws and other light bodies, as a magnet attracts iron. In the spirit which characterized the times, such effects were regarded with feelings of superstition. A soul was ascribed to amber, and it was held sacred.

(3.) Nor were these the only phenomena which presented themselves to the ancients, and afforded them a clue to the foundation of this part of physics.

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* Ἤλεκτρον, amber.

Various other scattered facts are recorded, which prove that Nature did not conceal her secrets with more than usual coyness in this case. The luminous appearance attending the friction of those substances which exhibited electrical effects, was observed. The Roman històrians record the frequent appearance of a flame at the points of the soldiers' javelins, at the summits of the masts of ships, and sometimes even on the heads of the seamen.* The effects of the torpedo and electrical fishes are referred to by Aristotle, Galen, and Oppian; and at a period less remote, Eustathius, in his Commentary on the Iliad of Homer, mentions the case of Walimer, a Gothic chief, the father of Theodoric, who used to eject sparks from his body; and further refers to a certain ancient philosopher, who relates of himself that on one occasion, when changing his dress, sudden sparks were emitted from his person on drawing off his clothes, and that flames occasionally issued from him, accompanied by a crackling noise.†

Such phenomena attracted little attention, and provoked no scientific research. Vacant wonder was the most exalted sentiment they raised; and they accordingly remained, while twenty centuries rolled away, barren and isolated facts upon the surface of human knowledge. The vein whence these precious fragments were detached, and which, as we have shown, *cropped out* sufficiently often to challenge the notice of the miner, continued unexplored and undiscovered; and its splendid treasures were reserved to reward the toil and crown the enterprise of our generation.

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* Cæsar, de Bell. Afr. cap. vi. Liv. cap. xxxii. Plut. Vita Lys. Plin. sec. Hist. Mun. lib. ii.

† Eustath. in Iliad, E.

(4.) The work of classification and generalisation was first commenced upon the phenomena of electricity by GILBERT, an English physician, in a work entitled *De Magnete,* published in the beginning of the seventeenth century. In this treatise, the substances then known to be susceptible of electrical excitement were enumerated, and several of the circumstances which affect the production of electrical phenomena, such as the hygrometric state of the atmosphere, were explained. Between that period and the earlier part of the last century the science was not advanced by any capital discoveries. In that interval, however, Otto Guericke, celebrated as the inventor of the air-pump, contrived the first electrical machine. This apparatus consisted of a globe of sulphur, mounted upon a horizontal axis, from which it received a motion of rotation, by means of a common handle or winch. The operator turned this handle with one hand, while with the other he applied a cloth to the globe, the friction of which produced the electrical state.

(5.) Aided by such apparatus, this philosopher discovered, that after a light substance has been attracted by and brought into contact with an electrified body, it will not be again attracted, but, on the contrary, will be repelled by the same body; but that after it has been touched by the hand, its primitive condition is restored, and it is again attracted. He also showed that a body becomes electric by being brought near to an electrified body without touching it; but offered no explanation of this fact, which, as will be seen hereafter, indicated one of the most important principles of electrical science.

(6.) Whether it was that his attention was altogether engrossed by the researches which he prosecuted with such splendid results in astronomy, the higher mechanics, and optics, or that facts had not yet accumulated in sufficient number and variety to impress him with a just notion of the importance of electricity as a general physical agent, NEWTON bestowed on it no attention. One experiment only proceeding from him is recorded, in which he shows that when one surface of a plate of glass is electrified, the attraction will be transmitted through the glass, and will be manifested by its effect on any light substances placed on the other side of it.

(7.) In the beginning of the eighteenth century, HAWKESBEE made a series of experiments on electrical light produced in rarefied air; but as no consequences were deduced from them affecting the progress of the science, we shall not further notice them. In the construction of the apparatus for producing electricity, he substituted a glass sphere for the globe of sulphur proposed by Otto Guericke. This was a considerable improvement; and yet the experimentalists who followed abandoned it, and used no more convenient apparatus than glass tubes, which were held in one hand, and rubbed with the other. To this circumstance Dr. Priestley ascribes, in a great degree, the slow progress made by the immediate successors of Hawkesbee in electrical discoveries.

(8.) About the year 1730 commenced that splendid series of discoveries which has proceeded with accelerated speed to the present day, and now forms the body of electrical science. Mr. STEPHEN GREY, a pensioner of the Charter House, impelled by a passionate enthusiasm, engaged in a course of experimental researches, in which were developed some general principles, which produced important effects on subsequent investigations.

(9.) The most considerable discovery of Mr. Grey was, that all material substances might be reduced, in reference to electrical phenomena, to two classes, *electrics* and *non-electrics;* the former, including all bodies then supposed to be capable of electric excitation by friction; and the other, those which were incapable of it. He also discovered that non-electrics were capable of acquiring the electric state by contact with excited electrics. As the experiments which led to these conclusions were of the highest interest, we shall here state them.

(10.) Desiring to make some experiments with an excited glass tube, he procured one about three feet and a half long, and an inch and a quarter in diameter. To keep the interior free from dust, he stopped it at the ends with corks. When this tube was excited, he happened to present one of the corks to a feather, and was surprised to observe that the feather was first attracted, and then repelled by the cork, in the way it was wont to be by the glass tube itself. He concluded from this, that the electric virtue conferred on the tube by friction passed spontaneously to the cork.

It then occurred to him to inquire whether this transmission of electricity would be made to other substances besides cork. With this view he obtained a deal rod about four inches in length, to one end of which he attached an ivory ball, and inserted the other in the cork, by which the glass tube was stopped. On exciting the tube, he found that the ivory ball attracted and repelled the feather even more vigorously than the cork. He then tried longer rods of deal; next rods of brass and iron wire, with like results. He then attached to one end of the tube a piece of common packthread, and suspended from the lower end of this thread the ivory ball and various other bodies, all of which he found capable of acquiring the electric state when the tube was excited. Experiments of this kind were made from the balconies of his house, and other elevated stations.

With a true philosophic spirit, he now determined to inquire what circumstances attending the *manner* of experimenting produced any real effect upon the results; and, first, whether the *position* or *direction* of the rods, wires, or cords, by which the electricity was transmitted from the excited tube, affected the phenomena. For this purpose he extended a piece of packthread in a horizontal direction, supporting it at different points by other pieces of similar cord, which were attached to nails driven into a wooden beam, and which were therefore in a vertical position. To one end of the horizontal cord he attached the ivory ball, and to the other he tied the end of the glass tube. On exciting the tube, he found that no electricity was transmitted to the ball, a circumstance which he rightly ascribed to its escape by the vertical cords, the nails supporting them and the wooden beam.

Soon after this, Grey was engaged in repeating his experiments at the house of Mr. Wheeler, who was afterwards associated with him in these investigations, when that gentleman suggested that threads of silk should be used to support the horizontal line of cord instead of pieces of packthread. It does not appear that this suggestion of Wheeler proceeded from any knowledge or suspicion of the electric properties of silk; and still less does it appear that Grey was acquainted with them; for, in assenting to the proposition of Wheeler, he observed, that "silk might do better than packthread on account of its smallness, as less of the virtue would probably pass off by it than by the thickness of the hempen line which had been previously used."

(11.) They accordingly extended a packthread through a distance of about eighty feet in an horizontal direction, supporting it in that position by threads of silk. To one end of this packthread they attached the ivory ball, and to the other the glass tube. When the latter was excited, the ball immediately became electric, as was manifested by its attraction upon metallic leaf held near it. After this, they extended their experiments to lines of packthread still longer, when the silk threads used for its support were found to be too weak, and were broken. Being under the erroneous impression that the escape of the electricity was prevented by the fineness of the silk, they now substituted for it thin brass wire, which they expected, being still smaller than the silk, would more effectually intercept the electricity; and which, from its nature, would have all the necessary strength. The experiment, however, completely failed. No electricity was conveyed to the ivory ball, the whole having escaped by the brass wire, notwithstanding its fineness. They now saw that the silk threads intercepted the electricity, because they were *silk*, and not because they were *small.*

Having thus accidentally discovered the insulating property of silk, they proceeded to investigate its generalization, and found that the same property was enjoyed by resin, hair, glass, and some other substances. In fact, it soon became apparent that this property belonged in a greater or less degree to all those substances which were then known to be capable of being rendered electrical by friction, and which were denominated *electrics.*

(12.) Grey now extended his inquiry to fluids and animal bodies. Having at that time no other test of the electrical state of a body than its attraction for light substances placed on a stand under it, the application of such a test to liquids presented at first some difficulty. This was soon surmounted by the expedient of blowing a soap-bubble from the bole of a tobacco-pipe. The bubble was held suspended over some leaf metal, and on bringing the excited tube to the small end of the pipe, the bubble immediately became electrical.

(13.) It was in the prosecution of these experiments that he discovered that, when the electrified tube was brought near to any part of a non-electric body, without touching it, the part most remote from the tube became electrified. He thus fell upon the fact, which afterwards led to the principle of INDUCTION. The science, however, was not yet ripe for that great discovery, and Grey accordingly continued to apply the principle of inductive electricity without the most remote suspicion of the rich mine whose treasures lay beneath his feet.

(14.) In another series of experiments, Grey was also unfortunate in missing a subsequent discovery on which he just touched. He found that certain electric bodies were capable of becoming permanently excited without the previous process of attrition. He took nineteen different substances, among which were resin, gum-lac, shell-lac, sulphur, and pitch, and the remainder of which were various compounds of these. The sulphur he melted in a glass vessel, the others in a spherical iron ladle. When they became solid, and cooled, and were removed from the moulds in which they were, in this manner, cast, he found them to be electrified, and that, on preserving them from exposure to the air, by wrapping them in paper or wool, this electrified state continued for an indefinite time. In the case of sulphur, he found that not only the sulphur was electrical, but also the glass from which it was removed. Had he carried these inquiries further, and looked carefully into the circumstances of the attraction exhibited by the sulphur and the glass, he could not have failed in discovering the existence of the two opposite electricities, and would probably have also found the reason why the iron ladle did not exhibit electrical signs as well as the glass. This, however, escaped him, and the honour of the discovery was reserved for a contemporary philosopher.

In his investigations respecting the power of liquids to receive electricity from excited glass, Grey exhibited, in a manner which at that period appeared striking, the attraction of the glass tube for liquids. We shall, however, pass over these and some other experiments of less importance, since they did not conduce to the development of any general principle.

(15.) Contemporary with Grey was the celebrated DUFAYE, who, though not impelled by the same enthusiasm, nor exhibiting the same unwearied activity in multiplying experiments, was endowed with mental powers of a much higher order, and consequently was not slow to perceive some important consequences flowing from the experiments of Grey, which had eluded the notice of that philosopher. Dufaye, in the first place, extended the class of substances called electrics; showing that all substances whatever, except the metals and bodies in the soft or liquid state, were capable of being electrified by friction with any sort of cloth, and that, to secure the result, it was only necessary to warm the body previously. He also showed that the property of receiving electricity by contact with an excited electric was much more general than was supposed by Grey, and that most substances exhibited that property in a greater or less degree, when supported by glass well warmed and dried. Dufaye also showed that the conducting power of the packthread used in the experiments of Grey depended on the moisture contained in it, and that the conducting power was considerably increased by wetting it. By this expedient he transmitted electricity along a cord to the distance of about 1300 feet.

(16.) It had been previously ascertained that when any substance charged with electricity communicated the electric principle to another body near it, but not in contact with it, the electricity passed from the one body to the other in the form of a spark, accompanied by a snapping or cracking noise, like that of a slight explosion. It had also been discovered by Grey and Wheeler, that the bodies of men and animals would become charged with electricity, if placed in the usual manner in contact with an excited glass tube, provided they were suspended by silk cords, so as to prevent the escape of the electricity. Dufaye, therefore, reasoned, that a man being so suspended by silk cords, the electricity imparted to his person could not escape; and being charged by the excited glass tube, sparks of fire ought to issue from his body, if any body capable of receiving the electricity were presented to it. To reduce this to the immediate test of experiment, Dufaye suspended his own person by silk lines; and being electrified, the Abbé Nollet, who assisted him in these experiments, presented his hand to his body, when immediately a spark of fire issued from the person of the one philosopher, and entered the body of the other. Although such a result had been predicted as a consequence of the arrangement, the astonishment was not the less great at its occurrence.

Nollet states that he can never forget the surprise of both Dufaye and himself when they witnessed the first explosion from the body of the former.

(17.) The celebrity of Dufaye rests, however, not on his experiments, but on the sagacity which led him to evolve natural laws of a high degree of generality from his own experiments, and from those of the philosophers who preceded him. He reproduced in a more definite form the principles of attraction and subsequent repulsion, which had previously been announced by Otto Guericke. "I discovered," says Dufaye, "a very simple principle, which accounts for a great part of the irregularities, and, if I may use the term, the caprices, that seem to accompany most of the experiments in electricity." This principle was, first, that excited electrics attract all bodies in their natural state; second, that after a body is so attracted, and has touched the excited electric, then such body is repelled by the excited electric; third, that if, after being so repelled, such body touches any other, it will be again attracted, and again repelled by the excited electric, and so on.

(18.) But a discovery of a much higher order was due to Dufaye. "Chance," says he, "threw in my way another principle more universal and remarkable than the preceding one; and which casts a new light upon the subject of electricity. The principle is, that there are two distinct kinds of electricity, very different from one another; one of which I shall call *vitreous*, and the other *resinous* electricity. The first is that of glass, rock-crystal, precious stones, hair of animals, wool, and many other bodies. The second is that of amber, copal, gum-lac, silk-thread, paper, and a vast number of other substances. The characteristic of these two electricities is, that they repel themselves and attract each other. Thus a body of the vitreous electricity repels all other bodies possessed of the vitreous, and on the contrary attracts all those of the resinous electricity. The resinous also repels the resinous and attracts the vitreous. From this principle one may easily deduce the explanation of a great number of other phenomena, and it is probable that this truth will lead us to the discovery of many other things."

This was a discovery of the highest order, and in its consequences fully justified the anticipation that "it would lead to the discovery of many other things." It is the basis of the only theory of electricity which has been found sufficient to explain all the phenomena of the science, and with the subsequent hypothesis of Symmer, and the laws of attraction developed by the researches of Coulomb, it has brought the most subtle and incontrollable of all physical agents under the subjection of the rigorous canons of mathematical calculation.

A new question now arose respecting any body which has been rendered electrical, whether by immediate excitation, or by contact with another body already excited. It was not enough to ascertain that it was electrified; but it was necessary to know with which of the two kinds of electricity it was invested. The test of this proposed by Dufaye was the same which has ever since his time been adhered to. He electrified a light substance freely suspended with a known species of electricity; say, for example, with resinous electricity. If this substance was repelled on bringing it near another electrified body, then the electricity of that body was known to be resinous; but if, on the contrary, it was attracted, then the electricity of the other body was known to be vitreous.

(19.) Dr. DESAGULIERS, whose works in other parts of physical science are well known, devoted some attention to electricity from the close of the labours of Grey till the year 1742, but the researches of this philosopher contributed nothing to the extension of the science. He methodised the elements which had already accumulated, and improved in some important instances the nomenclature. He denominated all substances in which electricity may be excited *electrics per se*, and defined in a distinct manner their characters. He also first applied the term *conductor* to bodies which freely transmitted electricity, and showed that animal substances owed this property to the fluids which they contain. He however failed to discover that moisture was the conducting agent in many other bodies which at that time were used to propagate electricity to a distance.

(20.) The subject of electricity now began to attract the attention of the Germans, and the first consequence was considerable improvement in the power and efficiency of electrical apparatus. The globe of glass revolving on an horizontal axis, which had originated with Hawkesbee, but had, ever since that time, greatly to the detriment of the science, been abandoned in favour of the glass tube, was now resumed by Professor Boze of Wittemburgh, who added, for the first time, the *prime conductor* to the machine. This conductor consisted of an oblong cylinder, or tube, of iron or tin. It was at first supported by a man, who was insulated by standing on cakes of rosin; but it was subsequently suspended by silken cords.

(21.) The method of exciting the globe or tube hitherto generally practised, and, indeed, long afterwards persevered in, was to rub them with the hand, taking care that it was dry and warm. Winkler, a professor in the university of Leipsic, substituted the more convenient expedient of a *cushion* fixed in contact with the globe, and gently pressed upon its surface by springs, or any similar means. Gordon, a Scottish Benedictine monk, who was professor of philosophy at Erfurt, abandoned the use of the *globe*, and substituted for it a *cylinder* of glass, having its geometrical axis horizontal, and supported on pivots so as to revolve on that axis. The cylinders he used were eight inches long, and four inches in diameter. Thus the electrical machine assumed a form very nearly identical with the cylindrical machines of the present day.

(22.) The effects produced by these improved and powerful apparatus are related to have been extraordinary. Various inflammable substances, such as spirits, heated oil, pitch, and wax, were fired. Appearances of electrical light issuing from points, and the experiment since known as the *electrical bells*, were the productions of this epoch. The spark drawn from the conductor by the finger is described as being so intense as to burst the skin, draw blood, and produce a wound. Other effects on the animal system are related, in which there is probably some exaggeration.

(23.) The year 1746 forms a remarkable epoch in the history of electricity, being signalized by the invention of the LEYDEN PHIAL. The merit of this discovery is disputed, being claimed for Professor MUSCHENBROEK, CUNEUS, a native of Leyden, and KLEIST, a monk of that place. Probably all these individuals were engaged in the proceedings in which the discovery originated. Dr. Priestley, a contemporary writer, gives an account of this invention, apparently obtained by personal inquiry, of which the following is the substance.

(24.) Professor Muschenbroek and his associates having observed that electrified bodies exposed to the atmosphere speedily lost their electric virtue, which was supposed to be abstracted by the air itself, and by vapour and effluvia suspended in it, imagined that if they could surround them with any insulating substance, so as to exclude the contact of the atmosphere, they could communicate a more intense electrical power, and could preserve that power for a longer time. Water appeared one of the most convenient recipients for the electrical influence, and glass the most effectual and easy insulating envelop. It appeared, therefore, very obvious, that water inclosed in a glass bottle must retain the electricity given to it, and that, by such means, a greater charge or accumulation of electric force might be obtained than by any expedient before resorted to. In the first experiments made in conformity with these views, no remarkable results were obtained. But it happened on one occasion that the operator held the glass bottle in his right hand, while the water contained in it communicated by a wire with the prime conductor of a powerful machine. When he considered that it had received a sufficient charge, he applied his left hand to the wire to disengage it from the conductor. He was instantly struck with the convulsive shock with which electricians are now so familiar, and which has been since, and is at present, so frequently suffered from motives of curiosity or amusement.

(25.) It is curious to observe how much effects on the organs of sense depend on the previous knowledge of them, which may or may not occupy the minds of those who sustain them. Those who now think so lightly of the shock, produced even by a powerful Leyden phial, would be surprised at the letter in which Muschenbroek gave Réaumer an account of the effect produced upon him by the first experiment. He states, that " he felt himself struck in his arms, shoulders, and breast, so that he lost his breath, and *was two days before he recovered from the effects of the blow and the terror.*" He declared, " that he would not take a second shock for the whole kingdom of France."

Nor was Muschenbroek singular in this extraordinary estimate of the effects of the shock. M. Allamand, who made the experiment with a common beer glass, stated that he lost the use of his breath for some moments, and then felt so intense a pain along his right arm that he feared permanent injury from it. Professor Winkler, of Leipsic, stated, that the first time he underwent the experiment he suffered great convulsions through his body; that it put his blood into agitation; that he feared an ardent fever, and was obliged to have recourse to cooling medicines! That he also felt a heaviness in his head, as if a stone were laid upon it. Twice it gave him bleeding at the nose, to which he was not subject. The lady of this professor, who appears to have been as little wanting in the curiosity which is ascribed to her own as in the courage assumed for the other sex, took the shock twice, and was rendered so weak by it that she could hardly walk. In a week, nevertheless, her curiosity again got the better of her discretion, and she took a third shock, which immediately produced bleeding at the nose.

No sooner were these experiments made known, than the amazement of all classes of people of every age, sex, and rank, was excited at what was regarded as "a prodigy of nature and philosophy." Philosophers everywhere repeated the experiment, but none succeeded in explaining its effects. After the first emotions of astonishment had abated, the circumstances which influenced the force of the shock were examined. Muschenbroek observed, that if the glass were wet on the outer surface the success of the experiment was impaired; and Dr. WATSON proved that the force of the shock was increased by the thinness of the glass of which the bottle containing the water was made. He also observed, that the force of the charge did not depend on the power of the electrical machine by which the phial was charged. Dr. Watson also showed that the shock could be transmitted undiminished through the bodies of several men touching each other.

(26.) By further repeating and varying the experiment, Watson found that the force of the charge depended on the extent of the external surface of the glass in contact with the hand of the operator; and it occurred to Dr. BEVIS that the hand might be efficient merely as a conductor of electricity, and in that case the object might be more effectually and conveniently attained by coating the exterior of the phial with sheet-lead or tin-foil. This expedient was completely successful; and the phial, so far as related to its external surface, assumed its present form.

Another important step in the improvement of the Leyden jar was also due to the suggestion of Dr. Bevis. It appeared that the force of the charge increased with the magnitude of the jar, but not in proportion to the quantity of water it contained. It was conjectured that it might depend on the extent of the surface of glass in contact with water; and that as water was considered to play the part merely of a conductor in the experiment, metal, which was a better conductor, would be at least equally effectual. Three phials were therefore procured and filled to the usual height with shot instead of water. A metallic communication was made between the shot contained in them respectively. The result was a charge of greatly augmented force. This was, in fact, the first electric battery.

(27.) Dr. Bevis now saw that the seat of the electric influence was the surface of contact of the metal and the glass, and rightly inferred that the form of a bottle or jar was not in any way connected with the principle of the experiment. He therefore took a common pane of glass, and having coated the opposite faces with tin-foil, extending on each surface within about an inch of the edge, he was able to obtain as strong a charge as from a phial having the same extent of coated surface. Dr. Watson being informed of this, coated large jars made of thin glass both on the inside and outside surface with silver leaf, extending nearly to the top of the jars, the effects of which fully corroborated the anticipations of Dr. Bevis, and established the principle that the force of the charge was in proportion to the quantity of coated surface.

The results of all these experiments led to the inference that, in the discharge of the phial, the electricity passed through the circle of conducting matter which was extended between the inside and the outside coating of the jar. If that circle were any where interrupted by the presence of non-conducting matter, or *electrics per se*, as they were then called, no discharge took place. Also, if any portion of the circle were formed of living animals, each animal sustained the shock. To carry the demonstration of this further, Dr. Watson placed, at several points in the circuit, spoons filled with spirits between the extremities of iron bars, but not in contact with them. In such cases the spirits in all the spoons were inflamed apparently at the instant of the discharge.

(28.) Many of these properties were simultaneously discovered by Mr. WILSON, who experimented in Dublin. He coated the external surface of the jar in the first experiments by plunging it in water. He also made several experiments with a view to affect by a shock one part of the human body without affecting the other parts. But the most remarkable discovery of this electrician was the *lateral* shock. He observed, that a person standing near the circuit through which the shock is transmitted, would sustain a shock if he were only in contact with any part of the circuit, or *even placed very near it.*

Those who are conversant with the science, and aware of the important principle of induction, will see, with much interest, how nearly many of the philosophers engaged in these researches touched, from time to time, on that property, and yet missed the honour of its discovery. Without it, the explication of the phenomenon of the charge and discharge of the Leyden phial was impossible. The lateral shock just adverted to, and observed by Wilson, was almost a *glaring instance* of it; but a still more striking manifestation of the theory of the Leyden phial was afforded by an experiment of Mr. CANTON, who showed that if a charged phial be insulated, the internal and external coatings would give alternate sparks, and then, by continuing the process, the phial might be gradually discharged. Canton just touched on the discovery of dissimulated electricity.

(29.) While these investigations were proceeding in England, the philosophers of France were not wanting in that zeal and activity which they have always manifested for the advancement of physical science. The Abbé Nollet, M. de Monnier, and others, prosecuted similar experimental researches, and arrived at the knowledge of several of the important circumstances developed in England. Nollet showed that a phial containing rarified air admitted of being charged as readily as one which contained water, and stated that the water in the Leyden experiment served no purpose, except to conduct the electricity to the glass.

(30.) From this time to the period at which Dr. Franklin commenced his researches, no important progress was made in the science, although at no former period were experiments on so grand a scale projected and executed; nor was public attention ever before so powerfully attracted to any scientific subject. Numerous and extensive experiments were made, both in England and France, to determine the distance through which the electric shock could be transmitted, the nature of the substances through which it could be propagated, and the rate at which it moved. At Paris, M. Nollet transmitted it through a chain of 180 soldiers; and at the convent of the Carthusians he formed a chain measuring 5400 feet, by means of iron wires extending between every two persons, and the whole company gave a sudden spring, and sustained the shock at the same instant.

(31.) But it was in England that the experiments on this subject were made on the most magnificent scale. Mr. Martin Folkes, then president of the Royal Society, Lord Charles Cavendish, Dr. Bevis, and several other fellows of the Society, formed a committee to witness these experiments, the chief direction and management of them being undertaken by Dr. Watson. A circuit was first formed by a wire carried from one side of the Thames to the other over Westminster Bridge. One extremity of this wire communicated with the interior of a charged jar; the other was held by a person on the opposite bank of the river. This person held in his other hand an iron rod, which he dipped into the river. On the other side, near the jar, stood another person, holding in one hand a wire communicating with the exterior coating of the jar, and in the other hand an iron rod. This rod he dipped into the river, when instantly the shock was received by both persons, the electric fluid having passed over the bridge, through the body of the person on the other side, through the water across the river, through the rod held by the other person, and through his body to the exterior coating of the jar. Familiar as such a fact may now appear, it is impossible to convey an adequate idea of the amazement, bordering on incredulity, with which it was at that time witnessed.

(32.) The next experiment was made at Stoke Newington, near London, where a circuit of about two miles in length was formed, consisting, as in the former case, partly of water and partly of wire. In one case there were about 2800 feet of wire, and 8000 feet of water. The result was the same as in the case of the experiment at Westminster Bridge. In this case, on repeating the experiment, the rods, instead of being dipped in the water, were merely fixed in the soil at about twenty feet from the water's edge, when it was found that the shock was equally transmitted. This created a doubt whether, in the former case, the shock might not have been conveyed through the ground between the two rods, instead of passing through the water, and subsequent experiments proved that such was the case.

(33.) The same experiments were repeated at Highbury, and finally at Shooter's Hill, in August, 1747. At the latter place the wire from the inside of the jar was 6732 feet, and that which touched the outside coating was 3868 feet long. The observers placed at the extremity of these wires were two miles distant from each other. The circuit, therefore, consisted of two miles of wire, and two miles of soil or ground, the latter being the space between the two observers. The result of the experiment proved that no observable interval elapsed between the moments at which each observer sustained the shock. In this experiment the wires were insulated by being supported on rods of baked wood.

We shall here pass over a variety of experiments made in England, France, and Germany on the effects of electricity on organized bodies, and on some proposed medical applications of that agent, such researches not having led to any general principles affecting the real advancement of the science.

(34.) Passing from the analysis of the confused experimental labours of his immediate predecessors, labours which contributed so little to the development of the nature and laws of electrical phenomena, to the researches of FRANKLIN, is like the transition from the mists and obscurity of morning twilight to the unclouded splendour of the noontide sun. It was in the summer of the year 1747, that a fortuitous circumstance, happily for the progress of knowledge, first drew the attention of this truly great and good man, and (as he afterwards proved) acute philo-

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sopher, to the subject of electricity. Mr. Peter Collinson, a fellow of the Royal Society of London, and a gentleman who took much interest in scientific affairs, made a communication to the Literary Society of Philadelphia, explaining what had been recently done in England in electrical experiments, and with his letter he sent a present of one of the glass tubes then commonly used to excite electricity, with directions for its use. Previous to this time, Franklin does not appear to have ever given his attention to physical science. Nevertheless he now commenced repeating the European experiments with all the ardour of an enthusiast, and extending, varying, and adapting them to the development of great general laws, with all the skill and sagacity of a practised experimental philosopher. Within the brief period of four months after the arrival of the tube, he commenced a series of letters to Mr. Collinson, in which are related a body of discoveries, which for the high generality of the laws they unfolded, the surpassing beauty and clearness of the experimental demonstrations on which they were based, and their intimate connection with the uses of life, are well worthy to be put in juxtaposition with the discoveries of Newton respecting the analysis and properties of light. How different, however, was the position of these two great discoverers and benefactors of the human race! One brought to bear on the subject of his inquiry a mind early disciplined in scientific investigation, a memory stored with profound mathematical erudition, faculties rendered more acute and strong by the severe studies exacted from all aspirants to academical honour and office in the universities of the old countries, zeal awakened, emulation stimulated, and enthusiasm kindled by associates, among whom were included all that was most distinguished in the physical sciences; the other, first a tallow-chandler's apprentice, and next a poor printer's boy, unschooled, undisciplined, self-informed, having nothing to aid him but the inborn energy of his mind, separated by an ocean three thousand miles wide from the countries which alone were the seats of the sciences, and where alone those aids and encouragements derivable from the society of others engaged in like inquiries could be obtained. Such was the individual whose researches we must now briefly notice. The series of letters in which he embodied the details of his experiments, and developed the laws which resulted from them, were continued from 1747 to 1754, and were subsequently collected and published.

(35.) "Nothing," says Priestley, "was ever written upon the subject of electricity which was more generally read and admired in all parts of Europe than these letters. There is hardly any European language into which they have not been translated; and, as if this were not sufficient to make them properly known, a translation of them has lately been made into Latin. It is not easy to say whether we are most pleased with the simplicity and perspicuity with which these letters are written, the modesty with which the author proposes every hypothesis of his own, or the noble frankness with which he relates his mistakes when they were corrected by subsequent experiments." *

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* History of Electricity, per. ix. sect. i.

(36.) In the analysis of Franklin's discoveries, it is necessary to distinguish carefully fact from hypothesis, and to separate the great natural laws which he brought to light, the truth and reality of which can never be shaken, based, as they are, on innumerable observed phenomena, from the theory by which these phenomena and their laws are attempted to be explained by him; which latter, though marked by great sagacity and ingenuity, and adequate to the explication of most of the ordinary effects of electricity, has been found insufficient to represent the results of subsequent researches, and has been generally superseded by another theory, which will be noticed hereafter.

(37.) The first step made by this philosopher in the brilliant series of discoveries by which he rendered his name so memorable, was one which produced a material influence on his subsequent proceedings, since it formed the foundation of his celebrated hypothesis of positive and negative electricity, which served him as the link by which many scattered facts might be grouped and connected, and as a clue to the development of new and unobserved phenomena. To reduce to the most brief, simple, and general terms the expression of the first-fruit of his observations, it may be said to consist in the establishment of the general principle, that when electricity is excited by the mutual friction or attrition of any two bodies, both these bodies become electrified; and if both are insulated they will continue to be so electrified. They will, however, be in different electrical states, since, if moveable, they would *attract* and not repel each other; but, nevertheless, each of them will exhibit in relation to other bodies not electrified the same properties. Thus sparks may be drawn indifferently from either; and each of them may be *de-electrised*, or discharged of their electricity, by being put in metallic communication with the ground. These general facts he proved by direct experiment.

(38.) He placed two persons, A. and B., on insulating supports. In the hand of A. he put a glass tube, which being rubbed by A. became electrified. This tube was then touched at every part of the rubbed surface by B.; after which the same process was several times repeated, the tube being deprived of its electricity as often as it was touched by B. A third person, C., not insulated, now presented his finger or a metallic sphere to B., from whom a spark was drawn; and by repeating this, or by touching the person of B., the latter was deprived of the electricity he had received from the tube. This was no more than was expected. But on subjecting A. to the same process, the very same effects were produced. It appeared, therefore, that both A. and B. were electrified.

Being again electrified, as before, by the friction of the tube, instead of A. and B. being successively touched by C., they were made to touch each other, both remaining insulated. After this both were found to be as completely *de-electrised* and restored to their ordinary state as when they had been touched by C.

A cork ball, suspended by a silk thread, being electrified by contact with the excited glass tube, was repelled when brought near the person of B., but it was attracted when brought near the person of A.

From these experiments it appeared the electrical states of A. and B. were different. Franklin called the state of B., and consequently that of the glass tube from which he drew the electricity, *positive,* and that of A. *negative.* The one was said to be *positively,* the other *negatively electrified.* The cloth with which A. rubbed the glass tube was, like A., negatively electrified—it attracted the cork ball; and the glass tube, like B., was positively electrified—it repelled the cork ball.

(39.) The generality of this result was established by a great variety of experiments. In all cases it appeared that the opposite electrical charges of the two bodies submitted to friction, or of any insulated bodies in communication with them, had the same reciprocally neutralising power; in virtue of which, when brought into contact, or when a metallic communication was established between them, all signs of electricity would disappear.

(40.) Such is a strict statement of the facts as evolved in the experiments. The hypothesis proposed by Franklin for their explication was as follows:—All bodies in their natural state are charged with a certain quantity of electricity, in each body this quantity being of definite amount. This quantity of electricity is maintained in equilibrium upon the body by an attraction which the particles of the body have for it, and does not therefore exert any attraction for other bodies. But a body may be invested with more or less electricity than satisfies its attraction. If it possess more, it is ready to give up the surplus to any body which has less, or to share it with any body in its natural state; if it have less, it is ready to take from any body in its natural state a part of its electricity, so that each will have less than their natural amount. A body having more than its natural quantity is electrified positively or *plus*, and one which has less is electrified negatively or *minus*.

When two bodies are submitted to mutual attrition and become electrified, one parts with a portion of its proper electricity, which is received by the other. The latter then has *more* than its natural amount, and is *positively* electrified; the former has *less*, and is *negatively* electrified.

In the instance above stated, when A. rubs the glass tube, he loses a portion of his natural electricity, and is negatively electrified; while the tube receives what he loses, and becomes *positively* electrified. When B. touches the tube, he takes from it nearly all the electricity with which it is charged over and above its natural amount; for his body being of so much greater magnitude than the tube, the proportion which will remain on the tube will be insignificant.

If when A. rubs the tube he were not insulated, he would not be electrified, because, as fast as his body would lose its proper amount of electricity, the deficiency would be made up from the earth with which he is in free electrical communication; whereas in the former case being insulated, this supply could not be obtained. Hence, in this theory, the earth is regarded as the common reservoir of electricity, from which bodies negatively electrified receive what they want, and to which bodies positively electrified give up their surplus, except in the case in which the one or the other are insulated.

Such, in general, was the Franklinian theory; which, however, will be more fully developed hereafter.

(41.) Assuming these hypothetical principles, Franklin next proceeded to analyse the phenomena of the Leyden jar. His first experiments were directed to establish the fact, that when the jar is charged the inside is electrified positively, and the outside negatively. A charged jar was placed on an insulating support, and a metallic wire bent into the form of a circular arc was then placed with one end in contact with the outer coating. The other end was capable of being brought into contact with the hook of the wire inserted through the cork, and thereby put in metallic communication with the water contained in the jar. This bent wire being supported by a handle of sealing-wax was itself insulated, and no electricity could pass in the experiment, otherwise than between the inside of the jar and the coating on the outside. On bringing the upper extremity of the bent wire into contact with the hook, the jar was instantly discharged, both the inside and the outside being restored to their natural state. Franklin inferred from this, that before the discharge the interior of the jar was *positively* electrified, and the exterior coating negatively electrified, in an equal degree; that is to say, that the interior of the jar contained an excess of electricity over and above its natural amount, and the exterior coating fell short of its natural amount by a quantity equal to that excess.

(42.) Various other experiments were made to verify this doctrine. Two metallic knobs were placed near each other, one communicating with the external coating, and the other with the water within the jar. A small cork ball suspended by a silk thread was placed between those two knobs. The ball was alternately attracted and repelled, "playing incessantly from one to the other, till the bottle was no longer electrised; that is, it fetched and carried fire from the top (inside) to the bottom (outside) of the bottle, till equilibrium was restored."*

It had been observed by electricians in Europe, that a jar could not be charged if its external coating were insulated; that, in fact, it was a necessary condition that a communication between that coating and the ground should be provided and maintained by some conducting matter, such as a metallic wire. Franklin assumes, that no electricity can be conveyed to the inside without causing the expulsion of an equal quantity from the outside; but if the jar be insulated, no means of escape being left for the electricity on the outside, no accumulation can take place on the inside.†

(43.) In these experiments, we find also a description of the method of charging a series of jars, now called the charge *by cascade*. "Suspend two or more phials on the prime conductor, one hanging on the tail of another, and a wire from the last to the floor. An equal number of turns of the wheel will charge them all equally, and every one as much as one alone would have been; what is drawn out of the tail of the first serving to charge (the inside of) the second; what is driven out of the second charging the third, and so on." *

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* Franklin's Works (Letters), vol. v. p. 192. Boston, 1837

† Ibid. p. 190.

(44.) In this way he constructed an electrical battery. After charging a series of jars he separated them, putting the insides in metallic communication with each other, and the outsides, in like manner, in metallic communication. By such means he obtained discharges sufficiently powerful to kill the smaller animals.

(45.) But the experiment which appeared to be most conclusive in the support it gave to his hypothesis, of the transfer of the electricity from the exterior to the interior of the jar in the process of charging it, was the following: — A jar was suspended by its hook on the prime conductor of the machine, so that a metallic communication was maintained between the conductor and the inside of the jar. Meanwhile, the rubber was insulated. On working the machine, the jar was found to receive no charge. A metallic wire was now rolled round the outer coating of the jar, and carried from thence to the rubber, so as to make a communication between them, both being still, in other respects, insulated. The jar was now charged with ease, which was explained by the supposition that the electric fluid passed from the outside coating by the wire to the rubber, and thence by the glass globe and prime conductor to the inside of the jar. †

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* Letters, p. 199.

† Ibid. p. 253.

(46.) According to the hypothesis above stated, there is no essential distinction, so far as relates to the charge, between the external coating and the internal contents of the jar; the one ought to be as easily charged as the other. This was accordingly found to be the case. A jar was placed on an insulating support, and while the external coating was put in communication with the prime conductor of the machine, the wire extending from the interior was put in communication with the rubber. The electricity of the outer coating was now positive, and that of the inside negative; and the jar was discharged, and produced the same effects as before.

(47.) The next important investigation was as to the place in which the electricity of the jar was contained. To determine this, Franklin charged a jar, and insulated it. He then removed the cork, and the wire by which the electricity was conveyed from the machine to the inside of the jar. On examining these, he found them free from electricity. He next carefully decanted the water from the charged jar into another insulated vessel On examining this it was found to be free from electricity. Other water in its natural state was now introduced into the charged jar to replace that which had been decanted; and on placing one hand on the outside coating, and the other in the water, he received the shock as forcibly as if no change had been made in the jar since it was first charged.*

A piece of glass was then placed between two plates of lead extending nearly to its edge on every side. One of these plates of lead being touched by the hand, the other was charged with electricity as usual. The plates were then removed from the glass, and, being examined, were found to be in their natural state. On presenting the finger to the glass where the lead had covered it, little sparks were received; and on displacing the lead, and touching it at both surfaces, a violent shock was received.

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* Letters, p. 201.

From this he inferred that the glass was the substance in which the electricity was deposited; and the metallic coating, or the water, or other conductor, applied to it, "served only, like the armature of the loadstone, to unite the forces of the several parts, and bring them at once to any point desired; it being the property of a non-electric (conductor), that the whole body instantly receives, or gives, what electrical fire is given to, or taken from, any one of its parts." *

(48.) From a very early period of the progress of electrical observations, the analogy between electricity and lightning had been noticed, and conjectures as to their identity were expressed; and in some cases distinct predictions hazarded, that the time would arrive which would fully establish their identity. Dr. Wall, in a paper published in the "Philosophical Transactions," speaking of the electricity of amber, said that he had no doubt, "that by using a longer and larger piece of amber, both the cracklings and the light would be much greater.

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* Letters, p. 202.

This light and crackling seems in some degree to represent thunder and lightning." *

(49.) Mr. Grey, whose experiments have been already referred to, says, speaking of electrical effects, "These are at present but in *minimis.* It is probable that, in time, there may be found out a way to collect a greater quantity of electric fire, and consequently to increase the force of that power, which, by several of these experiments, *si licet magnis componere parva*, seems to be of *the same nature* with that of *thunder and lightning.*"

(50.) But of all the anticipations which are pretended to of the grand discovery of the philosopher of Philadelphia, that which is by far the most remarkable proceeded from his contemporary and competitor, the Abbé Nollet. Immediately after the first exhibition of the experiments proving the identity of electricity and lightning, the Abbé urged his claim to a share of the merit of having suggested them. In a paper, dated Paris, June 6. 1752, the Abbé, after noticing the experiments, observes that he "is more interested than any one to come at the facts, which prove a true analogy between lightning and electricity, since these experiments establish incontestably a truth which he had conceived, and which he ventured to lay before the public more than four years ago."

In the fourth volume of his *Leçons de Physique* is found the following passage: — "If any one should undertake to prove, as a clear consequence of the phenomenon, that thunder is, in the hands of Nature, what electricity is in ours — that those wonders which we dispose at our pleasure are only imitations on a small scale of those grand effects which terrify us, and that both depend on the same mechanical agents — if it were made manifest that a cloud prepared by the effects of the wind, by heat, by a mixture of exhalations, &c. is in relation to a terrestrial object what an electrified body is in relation to a body near it not electrified, I confess that this idea, well supported, would please me much; and to support it, how numerous and specious are the reasons which present themselves to a mind conversant with electricity. The universality of the electric matter, the readiness of its action, its instrumentality and its activity in giving fire to other bodies; its property of striking bodies externally and internally, even to their smallest parts (the remarkable example we have of this effect even in the Leyden jar experiment, the idea which we might truly adopt in supposing a greater degree of electric power); all these points of analogy which I have been for some time meditating, begin to make me believe that one might, by taking electricity for the model, form to oneself, in regard to thunder and lightning, more perfect and more probable ideas than any hitherto proposed." *

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* Priestley, History of Electricity, p. 11.

The volume containing this passage was printed and published towards the close of the year 1748, as appears by the register of the Academy of Sciences, in which the order to print it bears date

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* Nollet, Leçons de Physique, tom. iv. p. 315., 8me. edition.

on the 9th of August in that year. It will presently appear that Franklin's first publication of the same views was in a letter addressed to Mr. Collinson, despatched in 1749. So far, therefore, as relates to these speculations, the priority of publication must be conceded to Nollet. It seems, however, improbable that Franklin, residing at Philadelphia, could have seen Nollet's volume between the date of its publication and the despatch of his letter, an interval not exceeding a few months; and the probability is, therefore, that these views occurred simultaneously to the American and the French philosopher.

(51.) From the moment that Franklin first engaged in electrical inquiries, his views were constantly bent on the discovery of some useful purpose to which the science could be applied. *Cui bono?* was a question never absent from his thoughts.* This craving after *utility* was the great characteristic of his mind, and might be regarded as being carried almost to a fault. To bring the properties of matter and the phenomena of Nature into subjection to the uses of civilised life, is undoubtedly *one* of the great incentives to the investigation of the laws of the material world; but it is assuredly a great error to regard it either as the only or the principal motive to such inquiries. There is in the perception of Truth itself — in the contemplation of connected propositions, leading by the mere operation of the intellectual faculties, exercised on individual physical facts, to the development of those great general laws by which the universe is maintained— an exalted pleasure, compared with which the mere attainment of convenience and utility in the economy of life is poor and mean. There is a nobleness in the power which the natural philosopher derives from the discovery of these laws, of raising the curtain of futurity, and displaying the decrees of Nature, so far as they affect the physical universe for countless ages to come, which is independent of all utility. There is a lofty and disinterested pleasure in the mere contemplation of the harmony and order of Nature, which is above and beyond mere utility. While, however, we thus claim for truth and knowledge all the consideration to which, on their own account, they are entitled, let us not be misunderstood as disparaging the great benefactors of the human race, who have drawn from them those benefits which so much tend to the wellbeing of man. When we express the enjoyment which arises from the beauty and fragrance of the flower, we do not the less prize the honey which is extracted from it, or the medicinal virtues it yields. That Franklin was accessible to such feelings, the enthusiasm with which he expresses himself throughout his writings in regard to natural phenomena abundantly proves. Nevertheless, *useful application* was, undoubtedly, ever uppermost in his thoughts; and he probably never witnessed any physical fact, or considered for a moment any law of nature, without inwardly proposing to himself the question, "In what way can this be made beneficial in the economy of life?"

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* After he had succeeded in making the discoveries which have been already explained, and besides inventing a little moving power, which he called an *electrical jack*, he expressed to Mr. Collinson, in his usual playful manner, his disappointment at being unable to find any application of the science beneficial to mankind. "Chagrined a little that we have hitherto been able to produce nothing in this way of use to mankind, and the hot weather coming on when electrical experiments are not so agreeable, it is proposed to put an end to them for this season, somewhat humorously, in a party of pleasure on the banks of the Schuylkill. Spirits, at the same time, are to be fired by a spark sent from side to side through the river without any other conductor than the water; an experiment which we some time since performed to the amazement of many. A turkey is to be killed for dinner by the *electrical shock*, and roasted by the *electrical jack*, before a fire kindled by the *electrified bottle*, when the healths of all the famous electricians of England, Holland, France, and Germany are to be drunk in *electrified bumpers*, under the discharge of guns from the *electrical battery*."—*Letters*, p. 210.

(*52.*) The analogy and probable identity of lightning and electricity were first suggested and demonstrated by Franklin in a letter addressed to Collinson, which appears without a date, and which has by some been referred to the date (1750) of that which immediately follows it in the published collection of letters. It appears, however, by a subsequent letter*, addressed to the same gentleman in 1753, that he was occupied in the investigation of this question from 1747 to 1749; that the paper now referred to was first written in the former year, but that it was enlarged and improved and sent to England in 1749, which must, therefore, be taken as its date. In this letter he enters very fully into his reasons for considering the cause of electricity and lightning to be the same physical agent, different in nothing save the intensity of its action; and he truly observes, that the difference in degree, however enormous, is no argument against the identity of the agents, but that, on the contrary, an almost infinite difference might be naturally looked for. "When a gun-barrel in electrical experiments has but little electrical fire in it, you must approach it very near with your knuckle before you can draw a spark. Give it more fire, and it will give a spark at greater distance. Two gun-barrels united, and as highly electrified, will give a spark at a still greater distance. But if two gun-barrels electrified will strike at two inches distance, and make a loud snap, to what a great distance may ten thousand acres of electrified cloud strike and give its fire, and how loud must be that crack!" *

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* "In my former paper on this subject, written first in 1747, enlarged and sent to England in 1749, I considered the sea as the great source of lightning," &c. — *Letters*, p. 300.

(53.) The analogies which he stated as affording presumptive evidence of the identity of lightning and electricity may be briefly enumerated. The electrical spark is zigzag, and not straight; so is lightning. Pointed bodies attract electricity; lightning strikes mountains, trees, spires, masts, and chimneys. When different paths are offered to the escape of electricity, it chooses the best conductor; so does lightning. Electricity fires combustibles; so does lightning. Electricity fuses metals; so does lightning. Lightning rends bad conductors when it strikes them; so does electricity when rendered sufficiently strong. Lightning reverses the poles of a magnet; he proved by direct experiment that electricity had the same effect. A stroke of lightning, when it does not kill, often produces blindness; he rendered a pigeon blind by a shock of electricity intended to kill it. Light-

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* Letters, p. 218.

ning destroys animal life; he killed a hen and a turkey by electrical shocks.

(54.) Having ascertained by experiment the property of points in attracting and discharging electricity, Franklin, acknowledging his inability to give satisfactory theory of this effect, set himself to inquire how "this power of points might possibly be of some use to mankind." To discover this, he suspended a large conductor, by silk lines, from the ceiling, and charged it with electricity, so as to enable it to give a spark at the distance of two inches, "strong enough to make one's knuckle ache." Under these circumstances, he found that if a person presented the point of a needle to the conductor at more than a foot distance, no electricity could be retained upon it, all passing off by the needle as fast as it was supplied. He also found, that if, after it was strongly electrified, the needle was presented at the same distance, the conductor would instantly lose its electricity. That the electricity, in this case, really passed off by the point, he ascertained by observing that, in the dark, the light was visible on the point of the needle; and also because, when the person presenting the needle was himself insulated, or stuck the needle in a bundle of sealing wax, the electricity no longer escaped.

(55.) The next experiment is so remarkable in itself, and so characteristic of the mind of Franklin, that we shall give it in his own words: —

"Take a pair of large brass scales, of two or more feet beam, the cords of the scales being silk. Suspend the beam by a packthread from the ceiling, so that the bottom of the scales may be about a foot from the floor; the scales will move round in a circle by the untwisting of the packthread. Let an iron punch (a silversmith's iron punch, an inch thick, is what I use) be put on the end upon the floor, in such a place as that the scales may pass over it in making their circle; then electrify one scale by applying the wire of a charged phial to it. As they move round, you see that scale draw nigher to the floor, and dip more when it comes over the punch; and, if that be placed at a proper distance, the scale will snap, and discharge its fire into it. But if a needle be stuck on the end of the punch, its point upwards, the scale, instead of drawing nigh to the punch and snapping, discharges its fire silently through the point, and rises higher from the punch. Nay, even if the needle be placed upon the floor near the punch, its point upwards, the end of the punch, though so much higher than the needle, will not attract the scale and receive its fire; for the needle will get it, and convey it away, before it comes nigh enough for the punch to act.

"Now, if electricity and lightning be the same, the conductor and scales may represent electrified clouds. If a tube (conductor) of only ten feet long will strike and discharge its fire on the punch at two or three inches distance, an electrified cloud of perhaps ten thousand acres may strike and discharge on the earth at a proportionally greater distance. The horizontal motion of the scales over the floor may represent the motion of the clouds over the earth, and the erect iron punch a hill or high building; and then we see how electrified clouds, passing over hills or high buildings at too great a height to strike, may be attracted lower till within their striking distance. And, lastly, if a needle fixed on the punch with its point upright, or even on the floor below the punch, will draw the fire from the scale silently at a much greater than the striking distance, and so prevent its descending towards the punch; or if in its course it would have come nigh enough to strike, yet, being first deprived of its fire, it cannot, and the punch is thereby secured from the stroke; *I say, if these things are so, may not the knowledge of this power of points be of use to mankind in preserving houses, churches, ships, &c. from the stroke of lightning, by directing us to fix, on the highest parts of those edifices, upright rods of iron, made sharp as a needle, and gilt, to prevent rusting; and, from the foot of those rods, a wire down the outside of the building into the ground, or down round one of the shrouds of a ship, and down her side till it reaches the water? Would not these pointed rods probably draw the electrical fire silently out of a cloud before it came nigh enough to strike, and thereby secure us from that most sudden and terrible mischief?*

(56.) "To determine this question, whether the clouds that contain lightning be electrified or not, I would propose an experiment to be tried, where it may be done conveniently. On the top of some high tower or steeple, place a kind of sentry-box, big enough to contain a man and an electrical stand. From the middle of the stand let an iron rod rise, and pass, bending, out of the door, and then upright twenty or thirty feet, pointed very sharp at the end. If the electrical stand be kept clear and dry, a man standing on it, when such clouds are passing low, might be electrified, and afford sparks, the rod drawing fire to him from a cloud. If any danger to the man be apprehended, let him stand on the floor of his box, and now and then bring near to the rod the loop of a wire that has one end fastened to the leads, he holding it by a wax handle; so the sparks, if the rod is electrified, will strike from the rod to the wire, and not affect him." *

When this and other papers by Franklin, illustrating similar views, were sent to London, and read before the Royal Society, they are said to have been considered so wild and absurd that they were received with laughter, and were not considered worthy of so much notice as to be admitted to a place in the "Philosophical Transactions."† They were, however, shown to Dr. Fothergill, who considered them of too much value to be thus stifled; and he wrote a preface to them, and published them in London. They subsequently went through five editions.

After the publication of these remarkable letters, and when public opinion in all parts of Europe had been expressed upon them, an abridgment or abstract of them was read to the Society on the 6th of June, 1751. It is a remarkable circumstance that, in this notice, no mention whatever occurs of Franklin's project of drawing lightning from the clouds. Possibly this was the part which had

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* Letters, p. 235.

† Franklin's Works (Memoirs), vol. i. p. 299.

before excited laughter, and was omitted to avoid ridicule.

(57.) Franklin was under an impression that a pointed rod could not be expected to attract the lightning, unless it were placed at a very great height in the atmosphere; and to render the result of his projected experiment more certain, he determined to wait for the completion of a spire then being erected in Philadelphia. Meanwhile, however, a different and more promising expedient occurred to him; which was, to send up the pointed wire upon a kite, by the string of which the lightning might be brought within his reach. He soon succeeded in realizing this, the most bold and grand conception which ever presented itself to the imagination of an experimental philosopher.

He prepared his kite by making a small cross of two light strips of cedar, the arms of sufficient length to extend to the four corners of a large silk handkerchief stretched upon them. To the extremities of the arms of the cross he tied the corners of the handkerchief. This being properly supplied with a tail, loop, and string, could be raised in the air like a common paper kite, and, being made of silk, was more capable of bearing rain and wind. To the upright arm of the cross was attached an iron point, the lower end of which was in contact with the string by which the kite was raised, which was a hempen cord. At the lower extremity of this cord, near the observer, a key was fastened; and, in order to intercept the electricity in its descent, and prevent it from reaching the person who held the kite, a silk ribbon was tied to the ring of the key, and continued to the hand by which the kite was held.

Furnished with this apparatus, on the approach of a storm, he went out upon the commons near Philadelphia, accompanied by his son, to whom alone he communicated his intentions, well knowing the ridicule which would have attended the report of such an attempt, should it prove to be unsuccessful. Having raised the kite, he placed himself under a shed, that the ribbon by which it was held might be kept dry, as it would become a conductor of electricity when wetted by rain, and so fail to afford that protection for which it was provided. A cloud, apparently charged with thunder, soon passed directly over the kite. He observed the hempen cord; but no bristling of its fibres was apparent, such as was wont to take place when it was electrified. He presented his knuckle to the key, but not the smallest spark was perceptible. The agony of his expectation and suspense can be adequately felt by those only who have entered into the spirit of such experimental researches. After the lapse of some time, he saw that the fibres of the cord near the key bristled, and stood on end. He presented his knuckle to the key, and received a strong bright spark. It was lightning. The discovery was complete, and Franklin felt that he was immortal.

A shower now fell, and wetting the cord of the kite, improved its conducting power. Sparks in rapid succession were drawn from the key, a Leyden jar was charged by it, and a shock given; and, in fine, all the experiments which were wont to be made by electricity were reproduced identical in all their concomitant circumstances.

(58.) This experiment was performed in the month of June, 1752. It will be remembered that Franklin's letters to Mr. Collinson had been previously published, translated, and widely circulated in different languages throughout Europe; and in these letters, not only the object of the experiment and the principle it was designed to establish were fully explained, but minute and circumstantial directions were given as to the manner of executing it. Persons engaged in physical inquiries in different parts of Europe were invited, and prepared to submit it to a trial when convenient opportunities offered. Among these was a French electrician, M. Dalibard, who, in the spring of 1752, prepared means of making the experiment at Marly-la-Ville, a place situate about six leagues from Paris. He succeeded on the 10th of May, about a month before the experiment of Franklin, and made a report of his proceedings to the Academy of Sciences at Paris on the 13th, in which he states that the experiment had been made at the suggestion and according to the method laid down by Franklin.* The experiment of Franklin, in June, was made before he could have been informed of that of Dalibard. The same experiment was repeated on the 18th of May by M. de Lor, at his house in the Estrapade, at Paris; and an account of it, as well as that of M. Dalibard, was communicated to the Royal

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* "En suivant la route que M. Franklin nous a tracée, j'ai obtenu une satisfaction complète." — *Mémoir de M. Dalibard,* quoted in Franklin's Works, vol. v. p. 288.

Society of London by the Abbé Mazeas, in a letter dated 20th May, two days after the latter experiment, in which the Abbé ascribes all the credit of the experiment to Franklin.*

(59.) The right of Franklin to the credit of having established the identity of lightning and electricity has been denied, and the honour claimed for the French philosophers Nollet and Dalibard. This claim was advanced, not when Europe from east to west, and from north to south, was filled with amazement and admiration at the philosophic boldness of the "Philadelphian experiment" (as it was universally called), or the profound sagacity with which it was conceived, with which its minute details were prescribed, and its results foretold—not when its illustrious author was elected by acclamation a member of the learned societies of Europe, and received the academical degree from the most ancient and honoured of universities—but after the lapse of nearly a century, after the story of Franklin's kite had passed from the transactions of philosophical societies, and the memoirs of institutes of sciences, into the primers of children. In short, it was so recently as the year 1831, that, in his admirable *Eloge* of Volta, M. ARAGO, taking a retrospect of electrical discovery, maintained that after the conjecture of Nollet, on the identity of lightning and electricity, an experiment to ascertain the fact was *almost useless*. And the reasons he assigned for such inutility were, that the experiment had been first made when flame appeared on the spears of soldiers, and the masts of ships*; but that, if any credit be claimed for the actual exhibition of the fact by immediate experiment, that credit is due to M. Dalibard.

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* See Phil. Trans. vol. xvii. 1752.

(60.) If such a statement, supported by such a reason, had proceeded from a quarter less entitled to respect than the "perpetual secretary of the Academy of Sciences," the astronomer royal of France, the man who stands, if not first, incontestably in the first rank of living meteorologists—in a word, than M. ARAGO—no one would think it entitled to a serious answer. It would be classed among those strange obliquities of historic vision which have led some persons to see in Richard and Macbeth, not tyrants and murderers, but mild and virtuous princes, cruelly wronged by the calumnies of tradition.

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* "Les premières vues de Franklin sur l'analogie de l'électricité et du tonnerre n'étaient, comme les idées antérieures de Nollet que de simples conjectures. Toute la différence, entre les deux physiciens, se réduisait alors à un projet d'expérience, dont Nollet n'avait pas parler. . . . . . . Sans porter atteint à la gloire de Franklin, je dois remarquer que l'expérience proposée était presque inutile. Les soldats de la cinquième légion Romaine l'avaient déja faite pendant la guerre d'Afrique, le jour où, comme César le rapporte, le fer de tous les javelots parut en feu à la suite d'un orage. Il en est de même des nombreux navigateurs à qui *Castor et Pollux* s'étaient montrés, soit aux pointes métalliques des mâts ou des vergues, soit sur d'autres parties saillantes de leurs navires. . . . . . . Au reste, soit que plusieurs de ces circonstances fussent ignorées, soit qu'on ne les trouvât pas démonstratives, des essais directs semblèrent nécessaires, et c'est à Dalibard, notre compatriote, que la science en a été redevable. Le 10 Mai, 1752, pendant un orage, la grande tige de métal pointue qu'il avait établie dans un jardin de Marly-la-Ville donnait de petites étincelles, comme le fait le conducteur de la machine électrique ordinaire, quand on en approche un fil de fer. Franklin ne réalisa cette même expérience aux Etats-Unis, à l'aide d'un cerf volant, qu'un mois plus tard." — *Eloge de Volta*, p. 12.

Nollet conjectured the probable identity of lightning and electricity, but gave not the most distant hint of any possible method by which the probability could be experimentally tested. Franklin boldly maintained the identity of these agents, gave numerous and cogent reasons to support that position, and moreover prescribed with minute details two distinct methods by which lightning could be brought into the hands of the observer, and submitted to the same experimental examination as electricity had undergone. One of these two methods was, in scrupulous accordance with his directions, applied in France; and the other, within a few weeks, was adopted by himself in America. The results of both were precisely what Franklin had foretold. Both were completely successful.

But, rejoins M. Arago, the whole affair of the experiment was useless, for it had already been effected. The flame on the javelins of the Roman sentinels of the fifth legion was sufficient as an experiment, not to mention *Castor* and *Pollux*, so often seen by sailors on their mast-tops! What would so severe a reasoner as M. Arago say to another who should maintain, without further experiment, that either of these luminous appearances was identical with lightning? — and if that were conceded, where would have been found the proof that these meteors, and the lightning with which they would be granted to be identified, were due to the same physical agent as that manifested by the friction of glass and resin?

If however, says M. Arago again, the experiment *were* necessary or useful, science owes it to M. Dalibard, who executed it at Marly-la-Ville a month before Franklin, with his kite, made it at Philadelphia. This statement is not attended with the circumstantial accuracy which M. Arago is accustomed to observe. The fact, as stated by M. Dalibard himself, was, that he took Franklin's printed directions as to the manner of performing his (Franklin's) projected experiment, and followed them to the letter in preparing his apparatus at Marly-la-Ville. Having accomplished this, he put the directions for making the observation into the hands of one Coiffier, an old retired soldier, who followed the trade of a carpenter, and who probably also erected the apparatus itself, and desired Coiffier to make the experiment in the manner prescribed by Franklin, if a storm should occur at a time when he (Dalibard) was absent. The first storm did occur when Dalibard was at Paris. Coiffier presented a piece of metal to the rod, and received several sparks. He then ran for the curé, who, with him, repeated the experiment, and immediately wrote a full description of it, with which he despatched Coiffier himself to Paris to M. Dalibard.

Thus it appears that so far from science being indebted to M. Dalibard for the earliest exhibition of this capital experiment, that philosopher had no other share in it, save that of having caused the erection of the conducting rod and other apparatus according to Franklin's directions. In the actual performance of the first experiment, he had no share whatever.

Let us now see how the account of credit stands on the score of this memorable discovery: —

In 1708, Dr. Wall mentions a *resemblance* of electricity to thunder and lightning.

In 1735, Mr. Grey *conjectures* their *identity*, and that they differ only in *degree*.

In 1748, the Abbé Nollet reproduces the conjecture of Grey, attended with more circumstantial reasons.

In 1749, Franklin strongly maintains their *identity*, and accurately describes two ways of experimentally testing it, and sends his instructions to Europe, to enable others with better local opportunities than he possessed to try it.

In 1752, MM. Dalibard and Delor, in France, make the preparations prescribed according to one of Franklin's methods; and Franklin makes in Philadelphia preparations according to the other method.

On 10th May, 1752, Coiffier and the curate make the experiment as directed by Franklin, and obtain the results foretold by Franklin.

In June, 1752, Franklin makes the same experiment in Philadelphia, according to the other method, with like results.

If the credit of the discovery is due to him who first *conjectured* the identity of lightning and electricity, then it is due to Mr. Stephen Grey.

If it be due to him who showed the method of making the capital experiment by which the identity must be either established or refuted, it belongs to FRANKLIN.

If it be due to the persons at whose expense Franklin's apparatus was first constructed, it must be shared between FRANKLIN, DALIBARD, and DELOR.

If it be due to him who first, in person, *performed* the experiment proposed by Franklin, it must be accorded to the carpenter and dragoon COIFFIER.

We shall now dismiss this matter, to which more space has been allotted than it is entitled to, merely observing, that much as living philosophers must be surprised at the claim advanced in favour of M. Dalibard, that electrician himself, could he rise from his tomb, would see with infinitely more astonishment an honour sought for him to which he never himself aspired, or supposed he had the slightest title.

(61.) Franklin having established, beyond the possibility of dispute, the identity of lightning and electricity, proceeded, in accordance with that characteristic attribute of his mind already noticed, to turn this discovery to the benefit of mankind, and proposed the general adoption of those pointed metallic rods now so commonly erected at the summits of buildings to protect them from the effects of lightning. The principle of this apparatus, as now constructed for edifices and ships, differs in nothing essential from that proposed by its celebrated inventor.

(62.) This part of the labours of Franklin in electricity cannot be dismissed without a passing notice of the dispute which was maintained in England respecting the comparative advantages of conductors with pointed ends as proposed by Franklin, or with round or blunted ends as suggested by some others. It were for the honour of science that this discreditable controversy had never taken place. It forms a rare, if not a solitary example, of the prostitution of philosophy to gratify the meanest passions of an obstinate and imbecile prince. The persevering tenacity with which the British monarch fastened his last grasp on his American subjects about to wrest themselves from his power, and assert their independence, is well known. By his pursuit of that object, after all reasonable hope of securing it had expired, the treasures of his kingdom were lavished, and the blood of his people flowed in mutual slaughter. Bad as were these consequences, they were nevertheless the ordinary consequences of war. But the vindictive spirit of the court passed from the field and council-board to the peaceful halls of science; and because Franklin, the agent, representative, and counsellor of the American people, had proposed the use of *pointed* conductors, a party of parasites was found, who, to gratify George III., advocated *blunt* conductors; and, to crown this most egregious absurdity, *blunt conductors* were actually erected upon the royal palace!*

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* "The king's changing his *pointed* conductors for *blunt* ones is a matter of small importance to me. If I had a wish about them, it would be, that he would reject them altogether as ineffectual. For it is only since he thought himself and his family safe from the thunder of heaven that he has dared to use his own thunder in destroying his innocent subjects." — *Franklin's Works*, viii. 227.

(63.) Franklin next directed his inquiries to the quantity and nature of the electricity with which the clouds in various states of the atmosphere were charged. To facilitate his experimental inquiries on this subject, he erected in his house in Philadelphia a pointed iron rod, which he was enabled to insulate at pleasure. This rod was put in communication with a system of bells, which alternately attracted and repelled their hammers when electrified. Whenever a cloud charged with electricity passed over the house within such a distance as to affect the conductor, these bells would ring and inform him of the opportunity of prosecuting his experiments.

(64.) Having satisfied himself that the clouds were frequently in an electrified state when there was no thunder or lightning, his next inquiry was, whether they were electrified positively or negatively. This was a question of more interest to him, because, according to his theory, if their electricity were negative, the earth, "in thunder-strokes, would strike into the clouds, and not the clouds into the earth." To determine this, he "took two phials and charged one of them with lightning from the iron rod, and gave the other an equal charge (of electricity) from the prime conductor. When charged, he placed them on a table within three or four inches of each other, a small cork ball being suspended by a fine silk thread from the ceiling, so as to play between the wires. If both bottles then were electrified *positively*, the ball being attracted and then repelled by the one must be repelled by the other. If the one *positively* and the other *negatively*, then the ball would be attracted and repelled by each, and continue to play between them, so long as any considerable charge remained." *

From experiments with this apparatus, he concluded that clouds were sometimes *positively* and sometimes *negatively* electrified, but oftener *negatively.* Electrical instruments had not yet, however, advanced to such a state of improvement as to enable a mind, even acute as his, to make much further discovery in atmospheric electricity; and although the details of his experiments and his theoretical speculations regarding them must always be read with profound interest, yet no further principles of importance appear to have been evolved from them.

(65.) If it be true that the Royal Society laughed at his speculations and refused to them a place in their Transactions, they were not slow to retract and repair their error. They conferred upon him their highest honour (the Copley medal), and unanimously elected him an honorary member of their society, in 1753.

(66.) An experiment so remarkable as the attraction of lightning from the clouds, could not fail to be verified and repeated by many enthusiastic lovers of science. One of the first instances of this zeal was rendered memorable by its fatal result. Professor George William Richmann of St. Petersburg was preparing an essay on electricity; and in order to obtain the most certain and accurate knowledge of the phenomena, he placed a conductor on his house, making a metallic communication between it and his study, where he provided means for repeating Franklin's experiments. On the 6th of August, 1753, while Richmann attended a meeting of the Petersburg Academy of Science, distant thunder was heard, on which he went to his house, accompanied by Sokolow the engraver, who being engaged to illustrate his work, desired to see those electrical appearances which he would have to represent in the plates. While Richmann was describing to Sokolow the nature of the apparatus, a thunder-clap was heard louder and more violent than any which had been remembered at St. Petersburg. Richmann stooped towards the electrometer of the apparatus to observe the force of the electricity, and " as he stood in that posture, a great white and bluish fire appeared between the rod of the electrometer and his head. At the same time a sort of steam or vapour arose which entirely benumbed the engraver, and made him sink on the ground." Several parts of the apparatus were broken in pieces and scattered about. The doors of the room were torn from their hinges, and the house shaken in every part. The wife of the professor, alarmed by the shock, ran to the room, and found her husband sitting on a chest, which happened to be behind him when he was struck, and leaning against the wall. He appeared to have been instantly struck dead.*

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* Letters, p. 302.

(67.) During 1752 and the succeeding years the subject of atmospheric electricity engaged the attention of persons devoted to physical science in different parts of Europe. The climate of England being less favourable to such researches than more southern latitudes, fewer opportunities of observation were offered; nevertheless, Canton, Wilson, and Bevis soon repeated and verified the Philadelphia experiments. Canton showed that the clouds were electrified, sometimes negatively and sometimes positively, and carried such observations further than Franklin.

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* Phil. Trans. vol. xlix. p. 61.

(68.) But the most acute and indefatigable follower of Franklin at this time, in atmospheric electricity, was Beccaria, who, in 1753, published a treatise on electricity at Turin, and a series of letters on the same subject at Bologna in 1758. He erected numerous conducting rods in different places of observation, and elevated kites according to Franklin's method. By raising these to various heights, he observed the electricity of different atmospheric strata, and he improved this mode of observation by interlacing the strings with metallic wire. To keep his kites constantly insulated, and, at the same time, to give them more or less string, he rolled the string upon a reel, which was supported by pillars of glass, and his conductors were placed in metallic communication with this reel.

(69.) This profound philosopher, and acute and accurate observer, has left in the history of electricity traces of his genius second only to those with which Franklin and Volta impressed it. Beccaria was the first who diligently studied and recorded the circumstances attending the phenomena of a thunder-storm. He observes that the first appearance of a thunderstorm (which generally happens when there is little or no wind) is one dense cloud or more, increasing rapidly in magnitude, and ascending into the higher regions of the atmosphere. The lower edge is black and nearly horizontal, but the upper is finely arched and well defined. Many of these clouds often seem piled one upon the other, all arched in the same manner; but they keep constantly uniting, swelling, and extending their arches. When such clouds rise, the firmament is usually sprinkled over with a great number of separate clouds of odd and bizarre forms, which keep quite motionless. When the thunder-cloud ascends, these are drawn towards it; and as they approach they become more uniform and regular in their shapes, till, coming close to the thunder-cloud, their limbs stretch mutually towards one another, finally coalesce, and form one uniform mass. But sometimes the thunder-cloud will swell and increase without the addition of these smaller adscititious clouds. Some of the latter appear like white fringes at the skirts of the thunder-cloud or under the body of it, but they continually grow darker and darker as they approach it.

When the thunder-cloud, thus augmented, has attained a great magnitude, its lower surface is often ragged, particular parts being detached towards the earth, but still connected with the rest. Sometimes the lower surface swells into large protuberances, tending uniformly towards the earth; and sometimes one whole side of the cloud will have an inclination to the earth, which the extremity of it will nearly touch. When the observer is under the thunder-cloud after it has grown large and is well formed, it is seen to sink lower and to darken prodigiously, and, at the same time, a great number of small clouds are observed in rapid motion, driven about in irregular directions below it. While these clouds are agitated with the most rapid motions, the rain generally falls in abundance; and if the agitation be very great, it hails.

While the thunder-cloud is swelling and extending itself over a large tract of country, the lightning is seen to dart from one part of it to another, and often to illuminate its whole mass. When the cloud has acquired a sufficient extent, the lightning strikes between the cloud and the earth in two opposite places, the path of the lightning lying through the whole body of the cloud and its branches. The longer this lightning continues, the rarer does the cloud grow, and the less dark in its appearance, till it breaks in different places and shows a clear sky. When the thunder is thus dispersed, those parts which occupy the upper regions of the atmosphere are spread thinly and equally, and those that are beneath are black and thin also, but they vanish gradually without being driven away by the wind.

The instruments for electrical observation used by Beccaria never failed to give indications corresponding to the successive changes in progress in the atmosphere above his observatory. The stream of fire from his conductor was generally uninterrupted while the thunder-cloud was directly above it. The same cloud in its passage electrified his conductor alternately with positive and negative electricity. The electricity of the conductor continued to be of the same kind so long as the thunder-cloud was simple and uniform in its direction; but when the lightning changed its place. a change in the species of electricity ensued. A sudden change of this kind would also happen after a violent flash of lightning; but the change would be gradual when the lightning was moderate, and the progress of the thunder-cloud slow.*

(70.) But among the labours of this philosopher, that rendered by modern discoveries most memorable was one which by his contemporaries and their immediate successors was regarded as an ingenious and over-refined conjecture, rather than what it afterwards proved to be, the distant shadow of a coming discovery detected by the far-sighted mind of this acute and extraordinary man. Franklin had been the first to magnetise fine sewing needles by the electric spark. Dalibard observed that the extremity of the needle at which the spark from the excited glass entered had northern polarity, and both Franklin and Dalibard discovered that a spark of equal force given to the other end of the needle deprived it of the magnetic virtue. From these and from similar experiments made by himself, Beccaria inferred that the polarity of the magnetic needle was determined by the direction in which the electric current had passed through it. He assumed the magnetic polarity acquired by ferruginous bodies which had been struck by lightning, as a test of the direction of the electric current in passing through them, and thence inferred the species of electricity with which the thunder-cloud had been charged.†

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* Beccaria, Lettere dell' Elettricismo. Bologna, 1758, p. 146. *et seq.*

† "I poli del mattone teste descritto, provano che anche in

(71.) Extending this analogy to the earth itself, Beccaria conjectured that terrestrial magnetism was, like that of the needle magnetised by Franklin and Dalibard, the mere effect of permanent currents of natural electricity, established and maintained upon its surface by various physical causes; that, as a violent current, like that which attends the exhibition of lightning, produces instantaneous and powerful magnetism in substances capable of receiving that quality, so may a more gentle, regular, and constant circulation of the electric fluid upon the earth impress the same virtue on all such bodies as are capable of it. Observation proves that a vast quantity of this fluid circulates between different parts of the atmosphere in storms; that a quantity not inconsiderable circulates in the time of ordinary rain; and that even when the weather is serene and the heavens unclouded, some quantity is still observable. "Of such fluid, thus ever present," observes Beccaria, "I think that some portion is constantly passing through all bodies situate on the earth, especially those which are metallic and ferruginous; and I imagine it must be those currents which impress on fire-irons, and other similar things, the power which they are known to acquire of directing themselves according to the magnetic meridian when they are properly balanced." *

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certi corpi che abbiano certa porzione di ferro, *il fulmine imprime un segno permanente della sua direzione.*" — *Beccaria, Lettere*, p. 261.

* "Di tale fuoco, io penso che alcuna parte perpetuamente discorra per tutti i corpi situati sopra la terra, massimamente per i metallici e ferigni. Penso che esso sia, il quale attra-

(72.) He observed, that to say we are insensible to this current around us, is no good argument against its existence; for that its uniformity, constancy, and universality would necessarily render it imperceptible, since all bodies must partake of it in common. His hypothesis to account for the *variation* and *dip* is not the least remarkable part of this extraordinary anticipation. He considers that the electro-magnetic currents have not all a common centre, but may have several situate in our northern hemisphere. The aberration of their common centre from the true terrestrial pole may probably be the cause of the variation of the compass. The periodical change to which the position of this common centre is subject would correspond with and cause the periodical change of that variation, and the obliquity of these currents may be the cause of the dip.*

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versando le padelle, le molle, le palette ed altri si fatti bislunghi ferri, i quali d'ordinario pendono o posano verticalmente, imprima loro la virtù di situarsi nella meridiana magnetica, allora che sono convenientemente bilicati."— *Lettere*, p. 266.

* " Questa sistematica elettrico-magnetica circolazione, secondo me, non procederebbe da un solo punto settentrionale, ma avrebbe infinite sorgenti in diversi punti del nostro settentrionale emisfero, forse successivamente, più folte nè luoghi più vicini ad alcun punto settentrionale; e la frequenza, la posizione, o piuttosto la direzione del corso loro mi si rappresenterebbono dalla posizione, frequenza, e diverzione, con che si dispongono intorno alli emisferi di una sferica calamita le ordinatissime filze della limitura di ferro. E giusta una tale ipotesi, l' aberrazione del centro comune di tutte le varie sorgenti, che estenderebbono la loro azione ad una data ragione, dal vero punto settentrionale mi spiegherebbe l' aberrazione della calamita; il periodo di quella aberrazione mi spiegherebbe il periodo di questa declinazione; l' obbliquità, con che

That the anticipation of the fundamental principle of electro-magnetism, and terrestrial magnetism, should have been complete in all its details, could scarcely have happened at that epoch without something approaching to inspiration; but it will be readily admitted that these guesses of BECCARIA, when compared with the discovery of OERSTED and the theory of AMPÈRE, form one of the most striking episodes in the history of science.

(73.) The analogy between lightning and the electric spark, arising from the peculiar noise or explosion with which each was attended, had been noticed by many electricians. Beccaria, however, investigated and demonstrated its cause, by showing that it proceeded from a pulsation produced in the air by the sudden displacement of that portion of it through which the electric fluid passes. This displacement being transmitted through the atmosphere in exactly the same manner as vibrations are produced by a sonorous body, the sound accompanying an electric discharge, and the thunder which attends the atmospheric electricity, ensue. Beccaria verified this hypothesis by experiment. He constructed a glass siphon, in one leg of which air was inclosed above a column of mercury, and compressed by the column in the other leg of the siphon. On discharging a Leyden jar through the air thus inclosed, the column of mercury in the other leg was suddenly elevated, and recovered its

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quelle sorgenti spiccierebbono da terra, e si direggerebbono verso mezzo dì, mi spiegherebbe e la inclinazione degli aghi, e la particolare facilità con che si calamitano i ferri si fattamente inclinati." — *Lettere*, p. 268.

position after several oscillations.* This fact was also noticed by Kinnersley, the friend and associate of Franklin, but not until a later period.

(74.) This was afterwards corroborated by Bouguer and De la Condamine, when they encountered a violent thunder-storm on one of the highest mountains of Peru. The cloud from which the thunder proceeded was placed at but a small distance above their heads. The thunder heard by them consisted only of single cracks, or explosions, like those which attend the discharge of electric batteries; an effect manifestly produced by the proximity of the cause of the sound, and the highly rarefied state of the air at that great elevation.

(75.) Contemporaneously with Beccaria, Franklin, and Canton, the subject of atmospheric electricity engaged the attention of Lemonnier, who erected an apparatus according to Franklin's method at St. Germain-en-Laye, with which he showed that sparks were received from the conductor not only in times of storm, but also when the heavens were cloudless. He also first showed that the electricity of the air underwent every twenty-four hours periodical variations of intensity.

(76.) Beccaria determined the law of these variations, and was the first who demonstrated that at all seasons, at all heights, and in every state of the wind, the electricity of an unclouded atmosphere is positive. He found no indications of electricity in the air in high winds, when the firmament was covered with black and scattered clouds, having a slow motion in a humid state of the air; but in the absence of actual rain, he found that in changeable squally weather, attended with occasional showers of snow, hail, or rain, the electricity was very variable, both as to its quantity and quality being sometimes feeble and sometimes intense; sometimes positive and sometimes negative.

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* Beccaria, Elettricismo Artificiale. Turin, 1753, p. 227.

(77.) Contemporaneously with Beccaria in Italy, Canton prosecuted inquiries in many respects similar in England, and in various matters of minor importance these philosophers arrived at the same results. The most considerable discovery due to Canton was, that the electricity developed in the friction of the same substance is not always of the same kind. It will be remembered that Dufaye gave the names *vitreous* and *resinous* to the two fluids, on the supposition that each was invariably produced by the friction of the classes of bodies signified by these terms. Canton, however, showed that glass itself was capable of being electrified negatively, and would be always so electrified, if the rubber used were the fur of a cat. Canton also (as well as Beccaria) proved that a volume of air in a quiescent state might be charged with electricity. To Canton is also due the discovery of the virtue of the amalgam of tin and mercury, still used with so much effect to augment the development of electricity on glass.

The progress of the science had now attained a point at which the great principle of induction could scarcely fail to force itself upon the notice of those engaged in electrical researches. A natural law of the highest order, embracing within the range of its application nearly the whole domain of electrical phenomena, its discovery and development, forms an epoch in the history of the science, scarcely second in importance even to that by which Franklin brought meteorology within the legislation of electricity. How much, then, will the veneration in which the memory of the philosopher of the West is held be increased, if it can be demonstrated, contrary to what has been generally maintained by the historians of the science, that to him is justly owing the honour of the discovery of this physical principle!

(78.) Some of the more obvious phenomena of induction were noticed so early in the progress of electrical science, as the researches of Mr. Grey; and many other effects proceeding from it presented themselves to subsequent experimental inquiries, but attracted no attention, and led to no consequences. The first series of experiments, conducted so as to develop in an unequivocal manner this principle, were laid before the Royal Society by Canton, on the 6th of December, 1753.* They consisted chiefly in rendering insulated conductors electrical, by bringing near to one end an excited glass tube, or stick of wax, and exhibiting the varying state of cork-balls suspended on the conductor by the alternate approach and removal of the excited electric.

(79.) These experiments having been communicated to Franklin, he pursued the inquiry, and succeeded in expressing, in clear and unequivocal terms, the principle of induction; that is to say, in demonstrating that a body charged with either kind of electricity will, on approaching a conductor in its natural state, render that part of such conductor which is nearest to it electrical; that its electricity will be contrary to that of the approaching electrified body; that on removing the electrified body the conductor would be restored to its natural state; all which effects Franklin showed would follow from his theory, by assuming that the electric fluid is self-repulsive, and attracted by the matter of the conductor.

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* Phil. Trans. vol. xlviii. p. 350.

(80.) The experiments and reasoning which appear to establish Franklin's right to the honour of this discovery are so concise, that they may be stated here nearly in his own words.

Let a metallic conductor, about five feet long and four inches in diameter, be suspended by dry silk lines, so as to be insulated. From one end of it suspend a tassel consisting of fifteen or twenty threads in a damp state, so as to give them a conducting power. Present an electrified glass tube within five or six inches of the opposite end, and keep it in that position for a few seconds. The threads of the tassel will diverge, and when the tube is withdrawn they will collapse.

While the tube is held near the opposite end of the conductor and the threads are divergent, present the finger to the end of the conductor at which the tassel is suspended. A spark will be received, and the threads of the tassel will collapse.

Let the tube be then removed. The threads of the tassel will again diverge.

Let the tube be again presented as before. The threads will again collapse, and so on.

Finally, let the tube be presented to the tassel. The divergence of the threads will immediately increase, and continue to increase, as the tube is brought nearer to the tassel.

These phenomena are accounted for by Franklin in the following manner: — "By taking the spark from the end of the conductor, you rob it of part of its natural quantity of electrical matter, which part so taken away is not supplied by the glass tube, and the conductor remains *negatively* electrified. On withdrawing the tube, the electric matter on the conductor recovers its equilibrium, or equal diffusion; and the conductor, having lost some of its natural electricity, the threads connected with it lose part of theirs, and so are electrified negatively, and repel each other.

"When the tube is again presented to the opposite end of the conductor, the part of the natural electricity which the threads had lost is again restored to them by the repulsion of the tube forcing the electric fluid towards them from other parts of the conductor, and thus restoring them to their natural state. When the tube is once more withdrawn, the fluid is again equally diffused, and the threads, as before, are negatively electrified.

"Finally, when the tube is presented to the threads already diverging with negative electricity, still more of their natural electricity is repelled by the excited tube, and the threads are more strongly negative than before, and their divergence is consequently augmented."

Pursuing the principle thus developed still further, Franklin now having restored the conductor to its natural state, presented the excited glass tube to the tassel. The threads immediately diverged.

Maintaining the tube in that position with one hand, he presented the finger of the other to the tassel. The threads receded from the finger as if repelled by it.

This was explained on the same principle. When the excited tube is presented to the tassel, part of the natural electricity of the threads is driven out of them into the conductor, and they are negatively electrified, and therefore repel each other. When the finger is presented to the tassel (being then close to the glass tube), part of its natural electricity is driven back through the hand and body, and the finger becomes, as well as the threads, negatively electrified, and so repels, and is repelled by them. To confirm this, hold a slender light lock of cotton, two or three inches long, near a conductor positively electrified. You will see the cotton stretch itself out towards the conductor. Attempt to touch it with the finger of the other hand, and it will be repelled by the finger. Approach it with a positively charged wire of a bottle, and it will fly to the wire. Bring it near a negatively charged wire of a bottle, it will recede from that wire in the same manner that it did from the finger, which demonstrates that the finger was negatively electrified as well as the cotton.*

(81.) The great principle thus thrown before the scientific world by Franklin, was immediately taken up and pursued through its consequences by WILKE and ÆPINUS, who carried on their researches together at Berlin. The most important result of their combined labours was the invention of the instrument, which, as subsequently improved under the hands of VOLTA, became the CONDENSER now so useful in electroscopical investigations.

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* Letters, p. 341. Also see Phil. Trans. vol. xlix. p. 300.

In applying the principle of induction to the phenomena of the Leyden jar, and to the same effect as exhibited by the oppositely electrified surfaces of a coated plate of glass, these philosophers saw that the negative state of one surface of the glass was, according to the Franklinian theory, the necessary consequence of the positive state of the other. This contrary state of the electricities could only be maintained on the supposition that glass was impermeable by the electric fluid; and Wilke and Æpinus reasoned, that to whatever extent air or any other body might be similarly impermeable, to the same extent might it be charged on its opposite surfaces. To realize this conception with a plate of air, they coated two large boards of equal size with tin-foil, and suspended them one over the other, leaving a space of about an inch in thickness between them. This space was, in fact, a plate of air, of which the upper and lower surfaces were in contact with the metallic coating of the boards. The lower board communicated with the ground, and a charge of positive electricity was given to the upper one. The lower one then became charged with negative electricity; and when a person touched at the same time the coating of the two boards, the equilibrium was re-established, and he received the shock produced by the passage of the electric fluid from the one to the other.

Many curious experiments were exhibited with this apparatus. They found that the two boards, when electrified, strongly attracted each other, and would have rushed together if they had not been prevented by the strings. Sometimes, when the charge was strong, the intervening plate of air was not sufficiently impermeable to resist the mutual attraction of the opposite electricities, and a spontaneous discharge would take place through it. They considered these two plates to represent the state of the clouds and the earth during a thunderstorm; the clouds being always charged with one kind of electricity, and the earth with the other, while the body of atmosphere between them was analogous to the stratum of air between the two boards. When the charges of the earth and clouds become so strong that the air can no longer resist the passage of the electric fluid through it, a spontaneous discharge ensues, the fluid is seen in its passage by the light it evolves, and the violent displacement of the air produced in its passage causes the thunder.

From these experiments, Æpinus inferred that the phenomena of the Leyden jar was not owing, as Franklin supposed, to any peculiar attraction of the glass for the electric fluid; for, since a plate of air might be charged as well as a plate of glass, that property must be common to them, and was not peculiar to the glass. He inferred, therefore, that this impermeability was a property of all nonconductors; and, since they can all receive electricity to a certain degree, it must consist in the difficulty and slowness with which the electric fluid moves in their pores, whereas, in perfect conductors, it meets with no obstruction at all.*

(82.) Æpinus brought to the investigation of the Franklinian theory of electricity those mathematical attainments in which its illustrious founder was deficient. The manner in which that theory had been assailed by its opponents, and defended by its partisans, was such as might have allowed interminable controversy. Æpinus first reduced its principles to exact mathematical statement, with a view to ascertain whether the consequences deducible from them, by rigorous calculation, should be in accordance with the observed phenomena, not only in their general character, but in their numerical quantity. He assumed, according to Franklin's hypothesis, that the molecules of the electric fluid were self-repulsive, and that they were attracted by those of the bodies on which they were diffused. He found, however, that the phenomena could not be explained on these suppositions, unless it were also assumed that between the matter composing the masses of different bodies there existed a mutually repulsive force, acting at sensible distances. At first he recoiled from an assumption in direct opposition to the known properties of matter; but the necessity for its admission, in order to give consistency and validity to the Franklinian theory, appears at length to have reconciled him to it.

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* Æpini Tentamen, &c. Petersburg, 1759, p. 82, 83.

(83.) The investigation of the physical relation between the principle of heat and that of electricity, had attracted the attention of experimental philosophers at a very early period in the history of electrical research. Beccaria suspected that heat might itself be an immediate means for the development of electricity, and made some experiments to illustrate this. He soon, however, relinquished the inquiry, concluding that, in cases where the appearance of electricity followed the application of heat, the effect was due to evaporation, or other physical agents, which ensued. Priestley observed that heat had some relation to the conducting power of bodies, since, by the elevation of temperature, that quality was improved.

(84.) A mineral substance, brought from the East by the Dutch navigators, called by the natives of Ceylon, where chiefly it was found, *Tournamal*, and since known as *Tourmaline*, exhibited, under certain circumstances, a property similar to that of amber, and other electrics. But the power was excited in it by mere elevation of temperature. Lemery, the Duc de Noia, Wilson, Priestley, and others, made experiments on this mineral, and published results, in which there were much discordance and contradiction. Æpinus first showed that the attraction and repulsion exerted by this gem when exposed to heat was owing to the development of electricity upon it; and that, when so excited, its opposite sides or ends had contrary kinds of electricity, one being always negative, and the other positive. This was the first case of the distinct exhibition of electrical polarity. Canton observed that the development of the electric fluid upon it was produced only by change of temperature, and that whenever the gem was broken each fragment exhibited the same electrical polarity.

(85.) At this period effects were observed, which, if chemical science had attained a sufficiently advanced state, could not fail to have led to the discovery of electro-chemistry. Beccaria, by the electric spark, decomposed the sulphuret of mercury, and recovered the metals, in some instances, from their oxides.* Watson found that an electric discharge passing through fine wire rendered it incandescent, and that it was even fused and burned. Canton, repeating these experiments with brass wire, found that, after the fusion by electricity, drops of copper only were found, the zinc having apparently evaporated. Beccaria observed that when the electric spark was transmitted through water, bubbles of gas rose from the liquid, the nature or origin of which he was unable to determine. Had he suspected that water was not what it was then supposed to be, a simple elementary substance, the discovery of its composition could scarcely have eluded his sagacity.

After general laws have once been developed, and their application to particular phenomena has become familiar, it appears wonderful that even quick-sighted and acute observers should have had such effects continually reproduced under their eyes, without even making an approach to the discovery of their causes. Franklin found that the

* Lettere del Elettricismo, § 341. p. 282.

frequent application of the electric spark had eaten away iron; on which Priestley observed, that it must be the effect of some acid, and suggested the inquiry, whether electricity might not probably *redden vegetable blues?* Priestley also observed that in transmitting electricity through a copper chain, a black dust was left on the paper which supported the chain at the points where the links touched it; and, on examining this dust, he found it to contain copper.

(86.) Some years after the invention of the Leyden jar, when the necessity of some sufficient indicator of the presence of electricity, and some visible measure of its power became apparent, the invention of electrometers engaged the attention of electricians. After several abortive attempts on the part of others, the Abbé Nollet proposed the simple expedient of suspending two threads, which, when electrified, would separate by their mutual repulsion. Cavallo afterwards improved upon this, by substituting two pith balls, suspended in contact by fine metallic wires,—an apparatus still used. After this, various forms of electroscopic instruments were suggested and constructed by Volta, Saussure, and others, all depending on the principle that the intensity of the electric fluid was manifested by the force of its attraction or repulsion exerted upon light substances to which it was imparted.

(87.) The principle of induction applied to the *air-condenser* by Wilke and Æpinus, was taken up by Volta, and applied, first, to the construction of the ELECTROPHORUS, and subsequently to the common CONDENSER, which, combined with the electroscope, became in electricity an instrument of investigation analogous in its character and importance to the compound microscope in optics.

(88.) The manner in which the electrified fluid is distributed upon insulated electrified conductors next became the subject of inquiry. Beccaria showed that its distribution is superficial, and that the internal parts of the electrified body are in their natural state. It was shown that, whether the electrified conductor were hollow or solid, the electricity contained on it was the same. Lemonnier first showed that the form of the conductor had an influence on the quantity and the distribution of the fluids.

(89.) In 1778 Volta published a memoir on this subject, in which he proved, that of two cylinders of equal superficial dimensions, that which had the greater length would receive, *cæteris paribus*, the stronger charge, and inferred that great advantage would arise from the substitution of a system of small cylinders for the large conductors of electrical machines. About the same period, he showed how inflammable gases could be ignited in close glass receivers by the electric spark, the apparatus for which purpose soon grew into his *eudiometer*, for the analysis of gases. Soon after this, the same apparatus supplied the means of inflaming a mixture of oxygen and hydrogen gas, which led to the discovery of the composition of water.

(90.) In the year 1759 appeared, in the "Philosophical Transactions," a series of papers by Mr. Robert Symmer, which are entitled to be recorded in the history of electricity; not so much on account of what they describe, as for the theoretical views developed in them. The experiments of Symmer consisted chiefly in exhibiting, by striking examples, the effect of the mutual attraction of bodies electrified by opposite kinds of electricity. These results led him to doubt the sufficiency of the Franklinian theory, then and long afterwards universally received, to explain satisfactorily the phenomena; and he was led to consider whether the hypothesis of Dufaye might not be so modified as to explain them more adequately. Dufaye, as has been already stated, assumed the existence of two independent electric fluids, which he supposed to be latent in two distinct classes of bodies, the one in bodies of a vitreous, and the other in bodies of a resinous nature; and that these fluids, while they were each self-repulsive, were mutually attractive of each other.

(91.) It was obvious that such an hypothesis was quite inconsistent with the known phenomena of electricity, even limited as they were in variety at the period now referred to. Symmer retained the supposition of Dufaye so far as regarded the assumed existence of two distinct fluids mutually attractive, but he maintained that these fluids were *not* independent of each other. On the contrary, he assumed that they were always co-existent in bodies not electrified; that, by their mutual attraction, they held each other in subjection; that every body in its natural state contained equal quantities of these fluids, each molecule of the vitreous fluid being combined with a molecule of the resinous fluid, the compound molecule thus formed exciting neither attraction nor repulsion on the other parts of the natural fluid.

This theory of two fluids was left by its author unsupported by any extensive application to the phenomena which could be expected to shake the confidence then generally given to the hypothesis of Franklin; and although it is noticed at some length in his History of Electricity by Dr. Priestley, it obtained no countenance or support until further advances in electrical experiments rendered apparent the defects of the theory of a single fluid. It may be here observed, that the French writers generally ascribe the theory of two fluids to Dufaye, and are silent as to Symmer's share in it; with what justice will be apparent from what has been above stated.

(92.) In the year 1770, Dr. Priestley published his works on electricity. This philosopher did not contribute materially to the advancement of the science by the development of any new facts; but in his History of Electricity he collected and arranged much useful information respecting the progress of the science. At this period the Honourable Henry Cavendish, whose name has been distinguished in other departments of physics, engaged in some original investigations respecting electricity. The discovery of the composition of water, by transmitting an electric spark through a mixture of oxygen and hydrogen gases, has been generally ascribed to him.* Cavendish conceived the notion of reducing the phenomena of electricity to mathematical analysis, and had proceeded with a memoir on that subject, which was completed before he learned that Æpinus had produced a work with the same object. On comparing his own paper with the *Tentamen* of Æpinus, he found that they were nearly similar. Nevertheless, Cavendish published his memoir.

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* This claim has been recently called in question. --- See Lardner on the Steam-engine. Seventh edition, p. 303.

(93.) The year 1785 formed an important epoch in the history of electrical science, marking, as it did, the commencement of those labours by which COULOMB laid the foundations of ELECTRO-STATICS This great experimental philosopher was the first who really brought the phenomena of electricity within the reach of numerical calculation, and thereby prepared the way for his followers in the same field to reduce this most subtle of all physical agents to the rigorous sway of mathematics. It is to COULOMB we owe it that statical electricity is now a branch of mathematical physics.

The immediate instrument by which this vast object was attained was the *balance of torsion*, which he had already used with signal success in other delicate physical inquiries. This apparatus, which will be fully explained in the following work, consisted of a needle suspended in a horizontal position by an extremely fine wire or filament of silk attached to its centre of gravity. The attraction, or other force of which the intensity is to be measured, is made to act on one end of this needle, so as to twist the filament by which it is suspended; and it is resisted in its effort to effect this by the reaction proceeding from the torsion so produced. This reaction, and therefore the force which produces it, and is in equilibrium with it, was proved by Coulomb to be proportionate to the angle described by the needle round its centre of motion. Such was the sensibility of this exquisite instrument, that it was found to be perceptibly affected by a force not exceeding the twenty-millionth part of a grain.

(94.) With this instrument Coulomb measured the force with which electrified bodies attract and repel each other; and the first result of his investigation was the discovery, that the law of this attraction and repulsion was the same which Newton showed to prevail among the great bodies of the universe. In fact, he showed that two bodies, oppositely electrified, attract each other with a force which, *cæteris paribus*, is the same at equal distances, and which augments in the same proportion as that in which the square of the distance is diminished. Also if two bodies be similarly electrified, they will repel each other by a force which increases according to the same proportion when the distance between them is diminished.

(95.) By attaching a very small circular disc of paper coated with metallic foil to an insulating handle, Coulomb found that by touching with the face of the disc an electrified surface, and then submitting the disc itself thus electrified by contact to the test of the balance of torsion, he could determine the depth of the electric fluid on the surface touched by the disc. In this manner was he enabled to *gauge* or *sound* the electricity on the surface of bodies, so as to compare numerically its depth on different bodies, or on different parts of the same body.

With this instrument he measured the proportion in which electricity was shared between insulated conductors when brought into contact, and also the law according to which its depth varied on different parts of the same insulated conductor. These results acquired, at a later period, still greater importance, supplying, as they did, tests by which the mathematical analysis of the science could be tried.

(96.) The same apparatus supplied the means of investigating the law according to which an insulated electrified conductor had its charge gradually diminished by dissipation in the surrounding air, and by the escape of the fluid by the imperfect insulation of the supports.

The results of the observations of Coulomb on the distribution of the electric fluid on the surfaces of conductors illustrated satisfactorily the doctrine of points, which formed so prominent a part of Franklin's researches. The theoretical solution of this problem was not, however, effected till a later period.

(97.) The demonstration of the identity of lightning and electricity naturally directed the attention of philosophers to the solution of other meteorological phenomena by means of the same agency. The explanation of the *aurora borealis* had long exercised the sagacity and baffled the attempts of those devoted to physical researches. Some ascribed this appearance to solar light refracted in the higher regions of the air, others assigned it to the agency of the magnetic fluid. Euler imagined it to proceed from the same ether which formed the tails of comets: Mairan conceived it to arise from the mixture of the atmosphere of the sun with that of the earth; but when the properties of electric light became known, and when its appearance in rarefied air had been observed, all these hypotheses were by common consent abandoned, and no doubt was entertained that, whatever might be the details of the natural process by which it was produced, the *aurora borealis* was an effect of atmospheric electricity. EBERHART, professor at Halle, and PAUL FRISI at Pisa, were the first who proposed an explanation of it, founded on the following facts:— "1. Electricity transmitted through rarefied air exhibits a luminous appearance, precisely similar to that of the aurora borealis."—"2. The strata of atmospheric air become rarefied as their altitude above the surface of the earth is increased." Hence they argued that the aurora is nothing more than electrical discharges transmitted through parts of the upper regions of the atmosphere, so rarefied as to produce that peculiar luminous appearance which they exhibit. This theory, which was embraced and improved in its details by Canton, Beccaria, Wilke, Franklin, and other contemporary electricians, has received further countenance from more recent researches.

Attempts were also made to explain on electrical principles other meteorological effects; such as waterspouts, whirlwinds, rain, fogs, hail, &c., but no satisfactory conclusions resulted from these investigations, and the discussion of such phenomena forms a part of the meteorological inquiry of the present time.

(98.) While the series of experimental researches which have just been related were in progress, many attempts were made to trace electricity in the phenomena of vegetable and animal life, and more especially to apply it as a medical agent in cases of organic disease in the animal system. None of these attempts, however, led to any consequences sufficiently important to entitle them to attention in this brief sketch.

(99.) After electroscopes had been much improved, and in their application to atmospheric electricity had derived great power from the addition of a long pointed conductor, extending from the diverging balls to a height of several feet, Volta engaged in the investigation of the electric state of the air. He substituted for the suspended balls two blades of dry straw, hanging in contact and communicating with the lower end of the conducting rod. In addition to this, he had recourse to another apparently strange and unusual expedient. He placed on the point of the rod a taper, so as to cause this conductor to terminate in a flame. He contended that the flame attracted to the point of the conductor three or four times as much electricity as would be collected in its absence. This was explained by the effect of the vertical current of air which the flame maintained directly over it, which established a better communication between the metallic conductor and the strata of air above it.

(100.) Assuming this property of flame, Volta argued, that since fires robbed the atmosphere above them of electricity faster and more effectually than metallic points, it must follow that to prevent coming storms, or to mitigate their force, the best expedient would be to light enormous fires in the middle of extensive plains, or, better still, on elevated stations. If the effects of the lamp on the atmospheric electrometer were admitted, there would be nothing unreasonable in the supposition that large fires may, in a short interval of time, rob immense volumes of air and vapour of their electricity.

(101.) Volta wished to submit this theory to an experiment on a large scale, but was not able to carry the design into effect. M. Arago suggested, that by making suitable meteorological observations in those parts of Staffordshire and other English counties which abound in vast iron furnaces, where fires of extraordinary magnitude are maintained night and day, and comparing the results with similar observations made in adjoining agricultural districts, the conjecture of Volta might be tested.*

Observations of this kind have accordingly been recently made both in England and in certain parts of Italy, the results of which will be explained at the proper place in these volumes.

(102.) It has been already stated, that direct observations proved that the atmosphere, in its ordinary condition, is always charged with positive electricity. The beginning of the year 1780 was signalised by a capital experiment, by which it was proved that the source from whence this vast amount of the electric fluid was derived, or, to speak more correctly, the cause of the disturbance of the general equilibrium of the globe, which gives a surplus of the positive fluid to the air, and leaves the earth surcharged with negative fluid, and which, in its effects, assumes all the terrific forms of the tempest and the hurricane, and probably of many other violent convulsions which are occasionally exhibited in the war of the elements, is to be found in the process of natural evaporation, which continually maintains its silent and imperceptible progress upon the surfaces of ocean, lake, and river, and even upon those of organized bodies. That heat passes off in a latent form by such means, and equalizes and moderates the general temperature around us, was well known ; but it was not suspected that the elements of the storm, the coruscations of meteoric light, and the splendours of the aurora were due to the same cause.

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* Eloge de Volta, p. 18.

Volta states, that in the year 1778 this idea occurred to him, and that he conceived the notion of an experiment by which it might be brought to an immediate trial. Let a metallic dish filled with water be placed on an insulating support, and exposed in the open air until it evaporates, the dish being maintained in communication with a sufficiently sensible condensing electroscope. If, in evaporating, the positive fluid be carried off, the dish will, after the evaporation, be negatively electrical, and the electroscope will show it ; if not, the electroscope will give no sign. Various circumstances prevented Volta from trying this experiment until the month of March, 1780, when, being in Paris, he succeeded, *in company with* some members of the Academy of Sciences. There appears, nevertheless, to remain some doubt as to the share which Volta really had in this famous experiment, since, in the account of it published by Lavoisier and Laplace, it is related as performed by them, and Volta is mentioned incidentally as being present on the occasion.*

(103.) After the phenomena of electricity had, by the labours of Coulomb, been reduced to exact numerical estimation, this branch of physics was in a state to permit its being brought within the pale of mixed mathematics. To accomplish this it was necessary to express, by mathematical formulæ, the intensity of the electric fluid on different parts of insulated conductors of given forms, placed either separately, or in such a position as to exercise an electrical influence upon each other without contact, or, finally, when placed in actual contact. To establish such formulæ, it was necessary to assume some definite hypothesis as the law of electrical action. The Franklinian theory of a single fluid appeared to be incapable of affording the means of explaining, with numerical precision, the state of such bodies. It is true, that this long-received hypothesis was sufficient to account, in a general way, for the electrical state of bodies under the ordinary circumstances of their mutual action; but when rigorous numerical accuracy was demanded, — when not merely the general circumstances of the dense accumulation of electricity in one part of the surface, its more feeble intensity at another, its total absence from a third place, or the presence of negative electricity on a certain side of a conductor, and positive electricity on another, were severally demanded; but when it was required to determine the *exact numerical measure of the depth of the fluid at each particular spot on a given insulated conductor*, placed under given conditions with reference to others, so that such numerical measure, so obtained by calculation, might be compared with the actual depth observed by the instruments invented and applied by Coulomb, then this theory appeared to fail; at least, none of its advocates produced any such calculations. La Place investigated, on mathematical principles, the distribution of electricity on ellipsoids of revolution, assuming, as the basis of his reasoning, the hypothesis of two fluids. Biot also investigated the same problem applied to spheroids of small eccentricity; but the general subjugation of this portion of electrical science to mathematical analysis is due to Poisson.

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* Eloge de Volta, p. 21.

This illustrious analyst took as the basis of his investigations the theory of two fluids proposed by Symmer and Dufaye, with such modifications and additions as were suggested by the researches of Coulomb. He regarded the mutual attractions and repulsions exhibited by electrified bodies, not as real forces exercised by those bodies, but as altogether due to the electric fluids with which they are charged. The laws of attraction and repulsion developed by Coulomb are therefore assumed as those of the electric fluids. The particles of each of these fluids are assumed to repel each other with a force varying according to that law, while the particles of each fluid attract those of the contrary fluid by a force governed by the same law. These conditions are sufficient to supply the mathematical formulæ necessary to the determination of the depth and quality of the electric fluid on every part of the surface of a body of given figure placed under any given electrical conditions. The electric fluids of either kind would, by virtue of their self-expansive property, escape from the surface of the body on which they rest; but this is prevented by the pressure of the surrounding air, which retains them in their position so long as their expansive force is less than that pressure. On bodies of elongated forms, or those which have edges, corners, or points, it is shown, as a consequence of this theory, that the electric fluid accumulates in greater depths about the ends, edges, corners, or points, than in other places. Its expansive force at such parts is therefore greater than elsewhere, and will exceed the atmospheric pressure, and escape when at other parts of the surface it is retained.

This theory will be explained in the present work, as far as its development is consistent with the object of these volumes. It will not, therefore, be needful to enlarge upon it further in this place. It may, however, be asked why it is, seeing that the theory of two fluids is sufficient for the explanation of all the phenomena to which it has yet been applied, and that, on the other hand, the theory of a single fluid fails to afford any satisfactory or accurate explanation of so many phenomena, the latter theory nevertheless still has followers, and that even among electricians, whose opinions cannot be regarded otherwise than with sentiments of respect, it is still clung to as the hypothesis best entitled to reception and confidence? It is not easy to assign any sufficient reason for this, unless one can be found in the profound and abstruse nature of the mathematical principles by the aid of which alone the effects are capable of being expressed. When it is remembered that, until very recently, electricity was regarded as exclusively a part of experimental physics; that researches in it were chiefly carried on by persons engaged in chemical investigations; that, from the nature of their studies and pursuits, such persons rarely cultivated even the elements of mathematics, and almost never pursued analytical science into those more profound parts which are now indispensable for the solution of the class of problems which electricity has presented,—it cannot be matter of much surprise that reasoning which is incapable of being expressed save by symbols, of which the force and import must be unintelligible to the great mass of such persons, should fail to carry conviction to their understanding. To arrive at such conviction, they must either commence their education anew, or be content to receive those new doctrines on their faith in the assurance of those who are capable of investigating them. Either side of such an alternative is never very willingly embraced.

Having now followed the progress of discovery in this part of electrical science to that point at which all subsequent researches must be regarded as the labour of our contemporaries, the province of the historian ceases. Whatever has been effected more recently will properly form a part of the subject matter of the volumes here presented to the reader, of which it is hoped that a brief exposition and analysis of the researches of contemporary philosophers will form not the least interesting and useful portion.

II. ELECTRO-DYNAMICS.

(104.) The investigation of the mechanical phenomena of material substances has been, in modern works, conducted by resolving these effects into two principal divisions; those in which the bodies exhibiting them are at rest, and those in which they are in motion. As applied to solid bodies, these divisions have been respectively denominated STATICS and DYNAMICS*; and, as applied to fluids, HYDROSTATICS and HYDRODYNAMICS. Electricity being assumed to be a physical agent, having the properties of an elastic fluid, and capable, like the grosser solids and fluids, of being maintained in a state of equilibrium by the mutual action and reaction of antagonist forces, or of moving in definite directions, and forming currents of greater or less intensity, the analysis of its effects would naturally be conducted by means of the same classification; and, accordingly, that division of the science in which the electric fluid is considered in a state of equilibrium or repose, and in which the physical conditions on which such equilibrium depends are investigated, would be denominated ELECTRO-STATICS, while that in which the effects of currents of electricity are considered would be called ELECTRO-DYNAMICS.

REST being in its nature more simple than MOTION, and the cases of forces mutually destructive of each other's influence, and therefore productive of equilibrium, being more simple than those in which motion ensues from the combined action of forces differing from each other in various respects, it was natural that, in every part of physics, the principles of statics should be first established and understood. Such has been accordingly the course which the progress of discovery has taken in other branches of natural philosophy, and electricity is not an exception to it. All the phenomena which have been hitherto adverted to in this notice belong properly to ELECTRO-STATICS. In all of them the electric fluid is contemplated in a state of equilibrium; or if its motion be occasionally considered, it is only in sudden and momentary changes from one state of equilibrium to another. Thus, when a Leyden jar is charged, the positive electricity accumulated on the inner surface of the glass is maintained there, in spite of the tendency it has to escape in virtue of its self-expansive property, by the attraction of the negative electricity accumulated on the external surface. When a communication is made between the internal and external surfaces by a metallic wire, this state of equilibrium ceases; the positive fluid of the inner surface runs along the wire in one direction, and the negative fluid of the external surface runs along it in the other direction, until each neutralises the other, and a new state of equilibrium is established by the actual combination of the two fluids. If this change occupied a sensible interval of time, and it were required to investigate the effects which would be produced during that interval either on the jar and wire, or on any bodies which might be within their influence, the question would properly belong to ELECTRO-DYNAMICS; but in fact the discharge, as it is called, or the transition from the one state of equilibrium to the other, is instantaneous, and the same may be said of all the phenomena which form the subject of the preceding pages.

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* The terms STEREO-STATICS and STEREO-DYNAMICS would be preferable.

In the commencement of this notice, the frequent influence of circumstances, apparently fortuitous, on the progress of discovery in the sciences has been mentioned. It would be difficult, either in the history of the sciences or of the political growth of states, to find a more signal example of this than was offered by the discovery of that powerful instrument of physical investigation, the VOLTAIC PILE. "It may be proved," says M. Arago, "that this immortal discovery arose in the most immediate and direct manner from a slight cold with which a Bolognese lady was attacked in 1790, for which her physician prescribed the use of *frog-broth*."

Galvani was professor of anatomy at Bologna. At the period just mentioned, it happened that several frogs, divested of their skins and prepare for cooking the broth prescribed for Madame Galvani, lay upon a table in the laboratory of the professor, near which at the moment stood an electrical machine. One of the professor's assistants, being employed in some process in which the machine was necessary, took sparks occasionally from the conductor, when Madame Galvani was astonished to see the limbs of the dead frogs convulsed with movements resembling vital action. She called the attention of her husband to the fact, who repeated the experiment, and found the motions reproduced as often as a spark was taken from the conductor. This was the first, but not the only or chief part played by chance in this great discovery.

(105.) Galvani was not familiar with electricity. Had he been so, he would have seen in the convulsions of the frog evidence of nothing more than a high electroscopic sensibility in the nerves of that animal, and an interesting example of the known principle of *electrical induction.* But luckily for the progress of science, he was more an anatomist than an electrician, and beheld with sentiments of unmixed wonder the manifestation of what he believed to be a new principle in the animal economy, and, fired with the notion of bringing to light the proximate cause of vitality, engaged with ardent enthusiasm in a course of experiments on the effects of electricity on the animal system. It is rarely that an example is found of the progress of science being favoured by the ignorance of its professors.

Chance now again came upon the stage. In the course of his researches he had occasion to separate the legs, thighs, and lower part of the body of the frog from the remainder, so as lay bare the lumbar nerves. Having the members of several frogs thus dissected, he passed copper hooks through part of the dorsal column which remained above the junction of the thighs, for the convenience of hanging them up till they might be required for the purposes of experiment. In this manner he happened to suspend several upon the iron balcony in front of his laboratory, when, to his inexpressible astonishment, the limbs were thrown into strong convulsions. No electrical machine was now present to exert any influence.

If the supply of capital facts be occasionally due to chance, or to the BEING by whom what is miscalled chance is directed, it is to the operation of the faculties of exalted minds that the development of the laws of nature is due: if rude lumps of the natural ore of science be now and then thrown under the feet of philosophy, the discovery of the vein itself, its depth and direction, its quality and value, the separation of the precious metal it contains from its baser elements, the demonstration of its connection with the phenomena of nature, and its adaptation to the uses of life, are all and severally the work of that noble faculty of intellect, that image of his own essence, which the Creator of the universe has impressed upon man, and which is never more worthily exercised than in the investigation of those laws of the material world, in all of which, whether they affect the vast bodies of the universe, or the imperceptible molecules of those around us, there is ever conspicuous a provident care for the wellbeing of his creatures.

In the convulsions of the frog, suspended by a copper wire on an iron rail, Galvani saw a *new fact,* and soon discovered that the circumstance on which it depended was the simultaneous contact of the metals with the nerves and muscles of the animal. He found that the effects were reproduced whenever the muscles touched the iron while the nerves touched the copper, but that contact with the copper alone did not produce them. He next placed the body of the animal upon a plate of iron, and touching the plate with one end of a copper wire, brought the other end into contact with the lumbar nerves. The convulsions followed as before. Galvani inferred from these and other similar experiments and observations, that the conditions under which the phenomenon was produced were, that a connection should be made between the nerves of the animal and the muscles with which those nerves were united by a continued line or circuit composed of two different metals; and he explained this singular effect by assuming, hypothetically, that, in the animal economy, there exists a natural source of electricity; that, at the junction of the nerves and muscles, the natural electricity is decomposed; that the positive fluid goes to the nerve, and the negative to the muscle; that the nerve and muscle are therefore analogous to the internal and external coating of a charged Leyden jar; that the metallic connection made between the nerve and the muscle in the experiments above mentioned serves as a conductor between these opposite electricities; and that, on making the connection, the same discharge takes place as in the Leyden experiment.

This theory fascinated for a time the physiologists. The phenomena of animal life had been ascribed to an hypothetical agent, which passed under the name of the "nervous fluid." The Galvanic theory consigned this term to the obsolete list; and electricity was now the great vital principle, by which the decrees of the understanding, and the dictates of the will, were conveyed from the organs of the brain to the obedient members of the body. Those who know how passionate is the love of a theory which appears to give a satisfactory account of effects otherwise mysterious, and how much more gratifying to the *amour-propre* it is to be able to connect effects with supposed causes, than to be compelled to view the former as the real limits of our knowledge, will understand the reluctance with which the Bolognese school and its distinguished leader would surrender a theory so dazzling as animal electricity; nevertheless, it was doomed soon to fall under the irresistible assaults of physical truth directed against it by a giant intellect, which, though located in a little village of the Milanese, belonged to mankind.

(106.) VOLTA, professor of natural philosophy at *Como*, and subsequently at Pavia, had been already known for his researches in different parts of physics, but more especially in electricity. The Bolognese experiments naturally engaged his attention, and it was not long before his superior sagacity enabled him to perceive that the theory of Galvani was destitute of any sound foundation. Indeed, a single experiment was sufficient to overturn it, though not to carry conviction of its futility to the minds of its partisans. Volta applied the metals in contact with each other to the muscle alone without touching the nerves, and the convulsions nevertheless ensued. The analogy of the muscle and nerve to the Leyden phial was no longer tenable. Volta transferred this analogy to the two metals, and contended that the mutual contact of two dissimilar metals must be regarded as the source of the electricity; that by the contact the natural electricity was decomposed, and the positive fluid passed to one metal, and the negative one to the other; and that the muscle merely played the part of a conductor in carrying off one of the fluids thus developed.

(107.) To this Galvani replied by showing that, when a single metal was used to connect the nerves and muscles the convulsions ensued, and that therefore the contact of dissimilar metals could not be the source of the electricity. Volta rejoined, that it was impossible to be assured of the perfect homogeneity of the metal, and that any the least heterogeneous matter contained in it would be sufficient for his hypothesis. Also, that when a single metal was used, the convulsions were uncertain, and never produced, except in cases where the organs were in the highest state of excitability; whereas, on the contrary, they happened invariably, and were long continued, when the connection was made by two dissimilar metals.

Tenacious of the cherished theory to the last, Doctor Valli, a partisan of Galvani, confounded the advocates of the school of Pavia, by showing that, by merely bringing the muscles themselves into contact with the nerves, *without the intervention of any metal whatever*, the convulsions ensued. To this, the expiring effort of the Bolognese party, Volta readily and triumphantly replied, that the success of the experiments of Valli required two conditions; 1st, that the parts of the animal brought into contact should be as heterogeneous as possible; and, 2dly, the interposition of a third substance between these organs. This, so far from overturning the theory of Volta, only gave it increased generality, showing, as it did, that electricity was developed, not alone by the contact of two dissimilar *metals*, but also by the contact of dissimilar substances not metallic.

From this time, the partisans of animal electricity gradually diminished, and no effort worth recording to revive Galvani's theory was made. Meanwhile, the hypothesis of Volta was, as yet, regarded only as the conjecture of a powerful and sagacious mind, requiring nevertheless much more cogent and direct experimental verification. This experimental proof he soon supplied.

(108.) The first analogy which Volta produced in support of his *theory of contact* was derived from the well-known experiment of Sulzer. If two pieces of dissimilar metal, such as lead and silver, be placed one above and the other below the tongue, no particular effect will be perceived so long as they are not in contact with each other; but if their outer edges be brought to touch each other, a peculiar taste will be felt. If the metals be applied in one order, the taste will be acidulous. If the order be inverted, it will be alkaline. Now, if the tongue be applied to the conductor of a common electrical machine, an acidulous or alkaline taste will be perceived, according as the conductor is electrified positively or negatively. Volta contended, therefore, that the identity of the cause should be inferred from the identity of the effects; that, as positive electricity produced an acid savour, and negative electricity an alkaline, on the conductor of the machine, the same effects on the organs of taste produced by the metals ought to be ascribed to the same cause.

(109.) However sufficient this analogy might seem to the understanding of Volta, it was insufficient for the rigid canons of the logic of modern physics, and he accordingly sought and obtained more direct and unequivocal proof of his hypothesis. Two discs, one of copper, and the other of zinc, were attached to insulating handles, by means of which they were carefully brought into contact, and suddenly separated without friction. They were then presented severally to a powerful condensing electroscope. The usual indications of electricity were obtained, and it was shown that this electricity was positive on the zinc, and negative on the copper. By repeating the contact, and collecting the electricity by means of the condenser, sparks were produced, and the demonstration was complete.

That the contact of dissimilar metals was followed by the evolution of electricity, could therefore no longer be doubted. It will, however, hereafter appear that philosophers are not even yet agreed that the contact is the immediate or the only cause of the disengagement of electricity in such cases. Chemical agency is now known to be one of the sources of electricity; and its operation is so subtle, often so imperceptible, and generally so inevitable, when heterogeneous molecules come into contact, that doubts have been entertained whether, in every case where electricity *seems* to proceed from contact, it has not really its origin in feeble and imperceptible chemical action.

Although the complete development of this last-mentioned idea belongs to a much more recent epoch in the progress of electrical discovery, yet the chemical origin of electricity did not altogether escape notice even at the period to which we now refer.

(110.) Of the numerous philosophers in every part of Europe who took part in the discussions, and varied and repeated the experiments connected with these questions, one of those to whom attention is more especially due was Fabroni, who, in the year 1792*, two years after the discovery of Galvani, communicated his researches to the Florentine Academy. In this paper is found the first suggestion of the chemical origin of Galvanic electricity.

Fabroni observes, that in the mutual contact of heterogeneous metals there is a reciprocal action which favours chemical change; that to this action must be ascribed many well-known phenomena, such as the more rapid oxidation of certain metals when combined, or in mere contact with other metals. According to him, a metal, like all chemical re-agents, has a tendency to combination with another metal when they are brought into contact; that this effect is only prevented by the superior force of cohesion which prevails among the particles of each. This cohesive force will, however, be lessened in its energy by the antagonism of the attraction of the molecules of the two metals towards each other, just in the same manner as it would be lessened by the action of heat. Being thus lessened, its opposition to the tendency which the particles of either metal have to combine with oxygen, taken either from the atmosphere, or obtained from the decomposition of water, would be proportionally diminished, and such oxidation would accordingly be promoted. In this way Fabroni accounted for the tendency of certain alloys of metal to oxidation, and for the well-known fact that iron nails, then used in attaching the copper sheathing to vessels, were rendered so liable to rust by their contact with the copper, that they became soon too small for the holes in which they were inserted. He supposed, therefore, that in the experiments of Galvani and Volta, in which the convulsions of the limbs of animals were produced, a chemical change was made by the contact of one of these metals with the liquid matter always found on the parts of the animal body; and that the immediate cause of the convulsions was not, as supposed by Galvani, due to animal electricity, nor, as assumed by Volta, to a current of electricity emanating from the surface of contact of the two metals, but to the decomposition of the fluid upon the animal substance, and the transition of oxygen from a state of combination with it to combination with the metal. The electricity produced in the experiments Fabroni ascribed entirely to the chemical changes, it being then known that chemical processes were generally attended with sensible signs of electricity. He maintained that the convulsions were chiefly due to the chemical changes, and not to the electricity incidental to them, which, if it operated at all, he considered to do so in a secondary way.

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* The date of the researches of this philosopher is generally, but erroneously, assigned to the year 1799.

The necessary limits of this notice will not allow of a further analysis of the researches of this philosopher; but if his original papers be referred to, it will be seen that he is entitled to the credit of having first distinctly demonstrated the chemical origin of Voltaic electricity.

(111.) In the year 1800, the attention of the scientific world was withdrawn from the controversy respecting the origin of Galvanic electricity, and all other matters of minor importance, and engrossed by one of those vast discoveries which constitute an epoch in the progress of knowledge, and give a new direction to the sciences. On the 20th March, 1800, Volta addressed a letter to Sir Joseph Banks, then president of the Royal Society, in which he announced to him the discovery of the VOLTAIC PILE, one of the most powerful instruments for the investigation of the laws of nature, as exhibited in the mutual relations of the constituent parts of matter, which ever did honour to the science of any age, or any nation.

In order to complete the experimental analysis of the effects of Galvanic electricity, Volta felt the necessity of collecting it in much greater quantities than could be obtained in the processes which had then been adopted. According to his theory, when two plates of metal, zinc and copper for example, were brought into contact, two currents of electric fluid originated at their common surface, and moved from that point in opposite directions. The positive fluid passed along the zinc, and the negative along the copper. If the extremities of the two metals most remote from their mutual contact were connected by an arc of conducting matter, these contrary currents would flow along this arc, the positive fluid moving from the zinc towards the copper, and the negative from the copper towards the zinc; but the intensity of these currents was supposed to be so feeble that no ordinary electroscope, whatever might be its sensibility, would be affected by it. In order to bring into operation in this question those instruments which had been applied to common electricity, he therefore sought some expedient by which he could combine, and, as it were, *superpose*, two or more currents, and thus multiply the intensity, until it should attain such an augmentation as to produce effects analogous to those which had been obtained by ordinary electricity.

With this object, he conceived the idea of placing alternately, one over the other, discs of different metals, such as zinc and copper. Let us suppose the lowest disc to be copper, having a disc of zinc upon it. On this disc of zinc let a second copper disc be placed, and over that a second disc of zinc, and so on. According to Volta's theory, currents of electricity would be established at each surface of contact of the two metals, the positive current running along the zinc, and the negative along the copper. With the arrangement above described, there would proceed from the first surface a negative downward, and a positive upward current; from the second a positive downward, and a negative upward current; from the third a negative downward, and a positive upward current, and so on; the downward current being negative, and the upward positive from the upper surface of each copper disc, and the upper current being negative and the downward positive from the lower surface of such disc. It is evident, therefore, that the downward currents would be alternately positive and negative; and the same would be the case with the upward currents. Now, since the surfaces of contact of the metals would be equal, these currents would have equal intensities, and accordingly each positive current would neutralize each negative current having the same direction. The result would be, that if the lowest and highest disc of the pile were of the same metal, all the currents neutralizing each other, the pile would evolve no electricity whatever; and if they were of different metals, all the downward currents, except one, would neutralize each other, and that one would be positive. The effect of the pile would therefore be the same as if it consisted of only two discs, one of copper, and the other of zinc.

Volta therefore saw the necessity of adopting some expedient by which all the currents in the same direction should be of the same kind; so that, for example, all the decending currents should be negative, and all the ascending currents positive. If this could be accomplished, the current issuing from the bottom of the pile would be a negative current as many times more intense than one proceeding from a single pair of discs as there were surfaces of contact supplying currents, and the same would be true of the positive current issuing from the top of the pile.

To effect this, it was necessary to destroy the Galvanic action at all those surfaces from which descending positive and ascending negative currents would proceed; that is, the lower surfaces of the copper discs and the upper surfaces of the zinc discs. But while this was effected, it was also essential that the progress of the descending negative and ascending positive currents should still be uninterrupted. The interposition of any substance which would have no sensible Galvanic action on either of the metals between each disc of copper and the disc of zinc immediately below it would attain one of these ends, since the action of all the surfaces in which ascending negative or descending positive currents could originate would thus be prevented. But in order to allow the free progress of the remaining currents in each direction, such substance must be a sufficiently free conductor of electricity. Volta selected, as the fittest means of fulfilling these conditions, discs of wet cloth. They would be free from any sensible Galvanic action on the metal, and their moisture would give them sufficient conducting power.

(112.) Having discovered the principles by which this species of electricity can be accumulated in quantity and strong currents obtained, he varied its form, and contrived the apparatus which is known by the name of *La Couronne de Tasses.* This arrangement, which Volta himself most commonly used in his experiments, consisted of a circle of cups filled with warm water, or a solution of sea-salt. He immersed in each cup a plate of zinc and one of silver, not in contact, and then established a metallic communication by means of wire between the zinc of one cup and the silver of the adjacent one. The positive fluid was found to proceed from the extreme zinc plate, and the negative from the extreme silver one, and a continuous current was obtained by connecting these by any conductors of electricity.

(113.) Profoundly impressed with the importance of the results likely to arise from the application of the powers of the pile in physical inquiries, and doubtless animated by the desire for which he was honourably distinguished to extend all possible encouragement and advantage to those engaged in the natural sciences, Napoleon, then first consul, and surrounded by the splendour of his southern triumphs, invited Volta to visit Paris; and there, at the Institute, before the *élite* of European philosophers, to explain personally his great invention, and expound his views as to its probable uses and powers as an instrument of scientific research. Volta accepted the proffered honour, and, in 1801, attended at three meetings of the Academy of Sciences, at which he explained his theory of contact, and developed his views respecting the *voltaic*, or, as he called it, *electro-motive*, action of different metals upon each other. Among the audience at these memorable meetings was Napoleon himself, and none present appeared to appreciate more justly the vastness of the power which was on that occasion placed in the hands of the experimental philosopher.

(114.) When the report of the committee on the subject was read, the FIRST CONSUL proposed that the rules of the Academy, which produced some delay in conferring its honours, be suspended, and that the gold medal be immediately awarded to Volta, as a testimony of the gratitude of the philosophers of France for his discovery. This proposition being carried by acclamation, the hero of an hundred fields, who never did things by halves, and who was filled with a prophetic enthusiasm as to the powers of the pile, ordered two thousand crowns to be sent to Volta the same day from the public treasury, to defray the expenses of his journey.* He also founded an annual medal, of the value of three thousand francs, for the best experiment on the electric fluid; and a prize of sixty thousand francs to him who should give electricity or magnetism, by his researches, an impulse comparable to that which it received from the discoveries of Franklin and Volta.

(115.) The relation in which the voltaic pile stood in reference to the Leyden jar and electrical machines now began to be perceived. In the latter apparatus a great quantity of electricity is accumulated on the surfaces of the jar, and held there in equilibrium, the positive fluid on one side of the glass, and the negative on the other. When the communication is made between the two surfaces, a torrent of the fluid precipitates itself instantaneously along the line of communication, and the electrical equilibrium is re-established in an interval of time so short as to be inappreciable. A sudden, instantaneous, and violent effect is produced on whatever bodies may be exposed to the transit of this electric fluid. On the other hand, the Voltaic pile is a generator of electricity, which supplies to its opposite poles the two fluids, the positive and the negative electricity, in a continued, gentle, and regulated current. It discharges it not suddenly or instantaneously, or with uncontrollable and irresistible violence, but with gentle, moderate, continued, and regulated action.

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* Arago, Eloge de Volta, p. 42.

What takes place in the Leyden jar in an interval so brief as to render observation of its progress, or examination of its successive effects impossible, is with the pile spread over as long an interval as the observer may desire. Besides this, the effects themselves consequent on the two modes of action are different. That which in mechanical phenomena is effected by a violent blow or concussion is not more different from the effects of the long-continued action of an uniform accelerating force or a constant pressure, than are the effects of the common electrical discharge from those of the currents of electricity propagated between the poles of the pile.

(116.) The physiological effects of electricity exhibited under these different forms, differ in a manner which might be anticipated from these modifications in the transmission of the electric fluid. If the wires proceeding from the opposite poles, and conducting the contrary currents of fluid, be taken in the hands, the sudden and violent shock of the Leyden jar is no longer felt. It is replaced by a continued convulsion in the arms and shoulders, which does not cease so long as the wires are held.

If a metallic plate, in connection with the positive pole, be applied to the tongue, and another connected with the negative pole to any other part, a strong acidulous savour is perceived. If the plate applied to the tongue be connected with the negative pole, a strong alkaline savour is felt.

It is not the organs of taste only which are sensible to the influence of this instrument. The sense of sight is susceptible of its operation in a manner even more wonderful. Let a metallic surface connected with one of the poles be applied to the forehead, the cheek, the nose, the chin, or the throat and, at the same time, let the patient take in his hand the wire connected with the other pole. Immediately a light will be perceived, even though the eyes be closed, the splendour and appearance of which will vary with the part of the face in contact with the metallic plate. By similar means, the perception of sound will be perceived in the ears.

The action of the pile on the animal body after the vital principle is destroyed is so well known, that it is scarcely necessary to mention it here. The trunk of a decapitated body will rise from its recumbent posture; the arms will move and strike objects near them; the legs will elevate themselves with a force sufficient to raise considerable weights; the breast will heave as if respiration were restored; and, in fine, all the vital actions will be manifested with terrific and revolting precision.

In the hands of the entomologist, the pile affords results not less interesting. The glow-worm, submitted to the electric current, shines with increased splendour; the grasshopper chirps, as if under the action of a stimulant.*

(117.) The physiological action of the pile was strongly suggestive of a mysterious connection between the electric fluid and the proximate principle of vitality. When some of these effects were exhibited to Napoleon, the emperor turned to Corvisart, his physician, and said, " Docteur, voilà l'image de la vie: la colonne vertébrale est la pile; le foie, le pôle negatif; la vessie, le pôle positif."*

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* Eloge, p. 33.

(118.) The invention of the pile had been scarcely more than hinted at, when that course of electro-chemical investigations began which soon led to the magnificent discoveries of Davy, and the series of experimental researches which have been continued to the present time with results so remarkable by those who succeeded him. The first four pages only of the letter of Volta to Sir Joseph Banks were despatched on the 20th of March, 1800; and as these were not produced in public till the receipt of the remainder, the letter was not read at the Royal Society, or published until the 26th of June following. The first portion of the letter, in which was described generally the formation of the pile, was shown in the latter end of April by Sir Joseph Banks to some scientific men, and among others to Sir Anthony (then Mr.) Carlisle, who was engaged at the time in certain physiological inquiries. Mr. W. Nicholson, the conductor of the scientific journal known as *Nicholson's Journal*, and Carlisle constructed a pile of seventeen silver half-crown pieces alternated with equal discs of copper and cloth soaked in a weak solution of common salt, with which on the 30th of April they commenced their experiments. It happened that a drop of water was used to make good the contact of the conducting wire with a plate to which the electricity was to be transmitted; Carlisle observed a disengagement of gas in this water, and Nicholson recognised the odour of hydrogen proceeding from it. In order to observe this effect with more advantage, a small glass tube, open at both ends, was stopped at one end by a cork, and being then filled with water was similarly stopped at the other end. Through both corks pieces of brass wire were inserted, the points of which were adjusted at a distance of an inch and three quarters asunder in the water. When these wires were put in communication with the opposite ends of the pile, bubbles of gas were evolved from the point of the negative wire, and the end of the positive wire became tarnished. The gas evolved appeared on examination to be hydrogen, and the tarnish was found to proceed from the oxydation of the positive wire. It was inferred that the process in which these effects were produced was the decomposition of water. This took place on the 2d of May, shortly after the receipt of the first portion of Volta's letter.

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* This anecdote was told by Chaptal, who was present on the occasion, to Bequerel; and the latter relates it in the first volume of his work on electricity, published in 1834. The idea that electricity is the immediate principle of vitality has occurred to other minds. Sir John Herschel, in his Preliminary Discourse published in the CABINET CYCLOPÆDIA in 1830, without any knowledge of the above anecdote, says (p. 343.), "If the brain be an electric pile constantly in action, it may be conceived to discharge itself at regular intervals, when the tension of the electricity developed reaches a certain point, along the nerves which communicate with the heart, and thus to excite the pulsation of that organ. This idea is forcibly suggested by the view of that elegant apparatus, the dry pile of De Luc, in which the successive accumulations of electricity are carried off by a suspended ball, which is kept by the discharge in a state of regular pulsation for any length of time." A similar idea occurred to Dr. Arnott, and is mentioned in his PHYSICS.

To ascertain whether the oxydation of the positive wire was an effect incidental to the experiment, or had an influence in producing the decomposition, Nicholson determined to try the effect of wires formed of metal more difficult of oxydation. Wires of platinum were accordingly inserted through the corks, and the experiment repeated. Bubbles of gas were now evolved from both wires. Two platinum wires were next inserted at the closed ends of two separate tubes, which, being open at the other ends and filled with water, were inserted in the same vessel of water. Being placed side by side close together, and the wires being continued to the lower ends of the tubes, so that the distance between their points was not more than two inches, their upper extremities were put in connection with the ends of the pile. Gas was evolved from the points of both wires, and, ascending through the water, was collected separately in the two tubes. These gases being examined, proved to be hydrogen from the negative, and oxygen from the positive wire, nearly in the proportion known to constitute water.*

Thus was the decomposing power of the pile established within a few weeks after the first intimation of the invention of that instrument had been received in England, and before any description of it had been published. It seemed proper to give these details here, not only on account of the great importance of the discovery, but because it has been sought to depreciate the merit of it by ascribing it altogether to chance. It is probably impossible to exclude chance altogether from such investiga-

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* Nicholson's Journal, vol. iv. p. 179. 1800.

tions, but in this there was as little as is gene
found.

(119.) When these experiments became known, Mr. W. Cruickshank of Woolwich repeated them, and obtained similar results; but observed that when the distilled water was tinged with litmus, the effects of an acid were produced at the positive and those of an alkali at the negative wire. Led by this indication, he tried the effects of the wires on solutions of acetate of lead, sulphate of copper, and nitrate of silver. In each case he found the metallic base deposited at the negative pole, and the acid manifested at the positive pole. Muriate of ammonia and nitrate of magnesia were next decomposed, the acid as before going to the positive, and the alkali to the negative pole. These experiments of Mr. Cruickshank were made as early as June, 1800.*

In the September following, Mr. Cruickshank published the continuation of his researches†, in which he corroborated the results of his former experiments, showing more generally the tendency of oxygen and the acids in Voltaic decomposition to collect round the positive wire, and hydrogen, metals, alkalies, &c. round the negative pole.

(120.) The investigations of which the pile became the instrument now began to assume an importance which rendered it necessary to give it considerably augmented power, either by increasing its height or enlarging its component plates. In either case, inconveniences were encountered which imposed a practical limit on the increase of its power. When the number or magnitude of the metallic discs was considerable, the incumbent pressure discharged the liquid from the intermediate discs of cloth or card. The trouble of refilling it whenever its use was required, and of wetting the cloth or card, was very great. Mr. Cruickshank, adopting the principle of Volta's *couronne des tasses*, proposed, as a more convenient form for the apparatus, an arrangement consisting of a trough of baked wood, which is a non-conductor of electricity, divided by parallel partitions into a series of cells. Into these cells the liquid to be interposed between the successive pairs of metallic plates was poured. A series of rectangular plates of metal, alternately zinc and copper, were arranged so as to be parallel to each other, and at such a distance as to allow the partitions of the trough to pass between each pair of plates. This modification rendered the Voltaic apparatus capable of having its power increased without practical limit.

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* Nicholson's Journal, vol. iv. p. 187. 1800.

† Ibid. p. 254.

(121.) While these investigations were proceeding, Ritter, afterwards so distinguished for his experimental researches, but then young and unknown, made various experiments at Jena on the effects of the pile; and, apparently without knowing what had been done in England, discovered its property of decomposing water and saline compounds, and of collecting oxygen and the acids at the positive, and hydrogen and the bases at the negative pole. He also showed that the decomposing power in the case of water could be transmitted through sulphuric acid, the oxygen being evolved from a portion of water on one side of the acid, while the hydrogen was produced from another separate portion of water on the other side of it.*

(122.) When the chemical powers of the pile became known in England, Sir Humphry (then Mr.) Davy was commencing those labours in chemical science which subsequently surrounded his name with so much lustre, and left traces of his genius in the history of scientific discovery which must remain as long as the knowledge of the laws of nature is valued by mankind. The circumstance attending the decompositions effected between the poles of the pile which caused the greatest surprise, was the production of one element of the compound at one pole, and the other element at the other pole, without any discoverable transfer of either of the disengaged elements between the wires. If the decomposition was conceived to take place at the positive wire, the constituent appearing at the negative wire must be presumed to travel through the fluid in the separated state from the positive to the negative point; and if it was conceived to take place at the negative wire, a similar transfer must be imagined in the opposite direction. Thus, if water be decomposed, and the decomposition be conceived to proceed at the positive wire where the oxygen is visibly evolved, the hydrogen from which that oxygen is separated must be supposed to travel through the water to the negative wire, and only to become visible when it meets the point of that wire; and if, on the other hand, the decomposition be imagined to take place at the negative wire where the hydrogen is visibly evolved, the oxygen must be supposed to pass invisibly through the water to the point of the positive wire, and there become visible. But what appeared still more unaccountable was, that in the experiment of Ritter it would seem that one or other of the elements of the water must have passed through the intervening sulphuric acid. So impossible did such an invisible transfer appear to Ritter, that at that time he regarded his experiment as proving that one portion of the water acted on was wholly converted into oxygen, and the other portion into hydrogen.*

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* Nicholson's Journal, vol. iv. p. 511.

(123.) This point was the first to attract the attention of Davy, and it occurred to him to try if decomposition could be produced in quantities of water contained in separate vessels united by a conducting substance, placing the positive wire in one vessel and the negative in the other. For this purpose, the positive and negative wires were immersed in two separate glasses of pure water. So long as the glasses remained unconnected, no effect was produced; but when Davy put a finger of the right hand in one glass and of the left hand in the other, decomposition was immediately manifested. The same experiment was afterwards repeated, making the communication between the two glasses by a chain of three persons. If any material principle passed between the wires in these cases, it must have been transmitted through the bodies of the persons forming the line of communication between the glasses.

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* Nicholson's Journal, vol. iv. p. 512.

The use of the living animal body as a line of communication being inconvenient where experiments of long continuance were desired, Davy substituted fresh muscular animal fibre, the conducting power of which, though inferior to that of the living animal, was sufficient. When the two glasses were connected by this substance, decomposition accordingly went on as before, but more slowly.

To ascertain whether metallic communication between the liquid decomposed and the pile was essential, he now placed lines of muscular fibre between the ends of the pile and the glasses of water respectively, and at the same time connected the two glasses with each other by means of a metallic wire. He was surprised to find oxygen evolved in the *negative*, and hydrogen in the *positive* glass, contrary to what had occurred when the pile was connected with the glasses by wires. In none of these cases did he observe the disengagement of gas either from the muscular fibre or from the living hand immersed in the water.

(124.) In October, 1800, after many experiments on the chemical effects of the pile, Davy commenced an investigation of the relation which its power had to the chemical action of the liquid conductor on the more oxydable of its metallic elements. The influence of chemical decomposition in evolving the Voltaic electricity originally maintained by Fabroni, was again brought under inquiry by Colonel Haldane. Davy showed that at common temperatures zinc, connected with silver, suffers no oxydation in water which is well purged of air and free from acids; and that with such water as a liquid conductor, the pile is incapable of evolving any quantity of electricity which can be rendered sensible either by the shock or by the decomposition of water; but that if the water used as a liquid conductor hold in combination oxygen or acid, then oxydation of the zinc takes place, and electricity is sensibly evolved. In fine, he concluded that the power of the pile appeared to be, in great measure, proportional to the power of the liquid between the plates to oxydate the zinc.*

He inferred from these results that although the exact mode of operation could not be accounted for, the oxydation of the zinc in the pile, and the chemical changes connected with it, were *somehow the cause of its electrical effects.*

(125.) To ascertain whether a liquid solution capable of conducting the electric current between the positive and negative wires of a Voltaic pile, but not capable of producing any chemical action on its metallic elements, would, when used between its plates, evolve electricity, Davy constructed a pile in which the liquid was a solution of sulphuret of strontia. When the current from an active pile was transmitted through the liquid, the shock was as sensible as if the communication had been made through water; but, on the other hand, solutions of the sulphurets were incapable of acting chemically on the zinc. If, therefore, chemical action on the zinc be a necessary condition to ensure the activity of the pile, such an arrangement must be inactive.

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* Nicholson's Journal, vol. iv. p. 337.

Twenty-five pairs of silver and zinc plates, erected with cloths moistened in solution of sulphuret of strontia, produced no sensible action, though the moment the sides of the pile were moistened with nitrous acid, the ends gave shocks as powerful as those of a similar pile constructed in the usual manner.

The next question brought to the test of experiment was, whether the chemical action which takes place between the liquid and the plates of the pile is of the same kind as that which is manifested when water is decomposed by its extreme wires; that is, whether, when the oxygen is freed upon the surface of the zinc, the remaining constituent of the solution decomposed is also liberated at the surface of the zinc, as in ordinary oxydation; or is transmitted invisibly through the fluid to the surface of the silver, and there deposited, or otherwise liberated, as in the decomposition between the positive and negative wires. An arrangement of zinc and copper plates, in the form of the *couronne des tasses*, was formed, and charged with spring water. The general result of these experiments showed that the hydrogen liberated by the zinc was manifested not at the zinc, but at the silver surface; and therefore that the action in the cells is similar to the decomposition of water at the extreme wires of the pile. The phenomena were, however, rendered less decisive of the question by the modifications produced by the azote of the common air combined with the water, and also by saline matter which it held in solution, effects which were then imperfectly understood.

(126.) The inventor of the pile maintained that, among the metals, those which held the extreme places in the scale of electro-motive power were silver and zinc; and that, consequently, these metals, paired in a pile, would be more powerful, *ceteris paribus*, than any other. But as he also showed that pure charcoal was a good conductor of the electric current, and that the electro-motive virtue depended on the different conducting powers of the metallic elements, it was consistent with analogy that charcoal, combined with another substance of different conducting power, would produce Voltaic action. Dr. Wells accordingly showed that a combination of charcoal and zinc produced sensible convulsions in the frog; and Davy, adopting this principle, constructed a *couronne des tasses*, consisting of a series of eight glasses, with small pieces of well-burned charcoal connected with zinc by pieces of silver wire, using a solution of red sulphate of iron as the liquid conductor. This series gave sensible shocks, and rapidly decomposed water. Compared with an equal and similar series of silver and zinc, its effects were much stronger. Hence he inferred that charcoal and zinc formed a combination equal, if not superior, to any of the metals.

(127.) Volta was understood to refer the electro-motive power of the metallic elements of the pile to the difference of their powers as conductors of electricity. The experiments of Davy induced him to connect the electro-motive power with the amount of chemical action on the more oxydable metal. These two principles might, nevertheless, be compatible, if it could be shown that the oxydation was dependent on, and proportional to, the difference of conducting power of the metals. To test this, it was only necessary to construct a pile with metals of nearly equal conducting power. With this view, Davy constructed a pile with gold and silver plates, these metals being supposed to differ very little in their power of conducting electricity, interposing discs of cloth moistened with dilute nitric acid. Voltaic action was produced. A similar pile, formed of plates of silver and copper, and a solution of nitrate of mercury, acted powerfully. The conducting powers of these several metals were then considered as nearly equal.*

(128.) In considering the various arrangements and combinations in which Voltaic action had been manifested, Davy observed, as a common character, that, in every case, one of the two metallic elements was oxydated, and the other not. Did the production of the electric current, then, depend merely on the presence of two metallic surfaces, one undergoing oxydation, separated by a conductor of electricity? and, if so, might not a Voltaic arrangement be made by one metal only, if its opposite surfaces were placed in contact with two different liquids, one of which would oxydate it, and the other transmit electricity without producing oxydation? To reduce this to the test of experiment with a single metallic plate would have been easy; but in constituting a series or pile, the two liquids, the oxydating and the non-oxydating, must be in contact, and subject to intermixture. To overcome this difficulty, different expedients were resorted to, with more or less success; but the most convenient and effectual method of attaining the desired end was suggested to Davy by Count Rumford. Let an oblong trough be formed, similar to that suggested by Cruickshank, as a substitute for the pile; and let grooves be made in it such as to allow of the insertion of a number of plates, by which the trough may be divided into a series of water-tight cells. Let plates of the metal of which the apparatus is to be constructed be made to fit these grooves; and let as many plates of glass or other non-conducting material, of the same form and magnitude, be provided. Let the metallic plates be inserted in alternate grooves of the trough, and the glass plates in the intermediate grooves, so as to divide the trough into a succession of separate cells, each cell having on one side metal, and on the other glass. Let such an arrangement be represented in *fig.* 1.,

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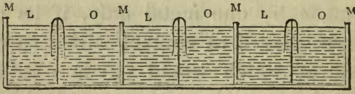
* The relative conducting power of the metals has not even yet been satisfactorily established.

Fig. 1.



where the metallic plates are represented at M, the intermediate plates being glass. Let the alternate cells O be filled with the oxydating liquid, and the intermediate cells L with the liquid which conducts without oxydating. Let slips of moistened cloth be hung over the edge of each of the glass tubes, so that its ends shall dip into the liquids in the adjacent cells. This cloth, or rather the liquid it imbibes, will conduct the electric current from cell to cell, without permitting the intermixture of the liquids.

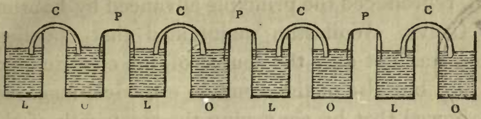
In the first arrangements made on this principle, the most oxydable metals, such as zinc, tin, and some others, were tried. The oxydating liquid O was dilute nitric acid, and the liquid L was water. In a combination consisting of twenty plates of metal, sensible but weak effects were produced on the organs of sense, and water was decomposed slowly by wires from the extremities. The wire from the end towards which the oxydating surfaces were directed evolved hydrogen, and the other oxygen.

To determine whether the evolution of the electric current was dependent on the production of oxydation, or would attend other chemical effects producible by the action of substances in solution upon metal, the oxydating liquid was now replaced by solutions of the sulphurets, and metallic plates were selected on which these solutions would exert a chemical action. Silver, copper, and lead were tried in this way. Solution of sulphuret of potash was used in the cells O, and pure water in L. A series of eight metallic plates produced sensible effects. Copper was the most active of the metals tried, and lead the least so. In these cases, the terminal wires produced, in the usual manner, the decomposition of water, the wire from which hydrogen was evolved being that which was connected with the end of the series to which the surfaces of the metal not chemically acted on were presented.

It will be observed that in this case the direction of the electric current relatively to the surfaces of the metallic plates was the reverse of the former. When oxydation was produced, the oxydating sides of the plates looked towards the negative end of the series. Comparing these two effects, Davy was led by analogy to suspect that if the cells O were filled with an oxydating solution, while the cells L were filled with a solution of sulphuret, or any other which would produce a like chemical action, the combined effect of the currents proceeding from the two distinct chemical processes would be obtained. This was accordingly tried, and the results were as foreseen. The acid solution was placed in the cells O, and the sulphuret in the cells L. A series, consisting of three plates of copper or silver, arranged in this way, produced sensible effects; and twelve or thirteen decomposed water rapidly. The oxydating sides of the metal looked to the negative end of the series.

(129.) As it appeared from former experiments that charcoal possessed, as a Voltaic agent, the same properties as the metals, the next step in this course of experiments was naturally to try whether a Voltaic arrangement could not be constructed without any metallic element, by substituting charcoal for the metallic plates in the series above described. This was accomplished by means of an arrangement in the form of the *couronne des tasses*. Pieces of charcoal, made from very dense wood, were formed into arcs; and the liquids O and L were arranged in alternate glasses, as represented in *fig.* 2. The charcoal arcs C were placed so as

Fig. 2.



to have one end immersed in each liquid, the intermediate glasses being connected by slips of bibulous paper P. When the liquid O was dilute acid, and L water, a series consisting of twenty pieces of charcoal gave sensible shocks, and decomposed water. This arrangement also acted, and with increased intensity, when the liquid O was sulphuric acid, and L was solution of sulphuret of potash.

(130.) The connection of chemical change with the production of electricity in the pile, was too obvious not to attract the attention of other philosophers. Pepys in England, and MM. Biot and Frederic Cuvier in France, investigated the effect produced by the pile on the atmosphere in which it was placed. The former placed the pile in an atmosphere of oxygen, and found that in the course of a night 200 cubic inches of the gas had been absorbed. In an atmosphere of azote the pile had no action. MM. Biot and Cuvier also observed the quantity of oxygen absorbed, and inferred from their experiments that " although, strictly speaking, the evolution of electricity in the pile was produced by oxydation, the share which this had in producing the effects of the instrument bore no comparison with that which was due to the contact of the metals, the extremity of the series being in communication with the ground."

(131.) Dr. Wollaston and Gautherot, on the other hand, reproduced the principle advanced by Fabroni and Crève. Wollaston maintained that chemical action was not only the source of the electricity of the pile, but also of the common electrical machine. He showed that by conveying the electricity of the machine to gold wires terminated in extremely fine points the decomposition of water could be effected, and that the phenomenon was the same as when the decomposition was effected by Voltaic wires. He maintained that the friction of the rubber was attended with oxydation, and showed that the machine was ineffective in an atmosphere of dry hydrogen, or any other gas in which chemical action was not produced.

(132.) If an oblong slip of wet paper have its extremities in contact with the poles of a Voltaic pile, each half of the slip will be electrified; that which is in contact with the positive pole will be positively electrified, and that which is in contact with the negative pole will be negatively electrified. If it be removed from contact with the pile by a rod of glass, or other nonconductor, its electric state will continue. This means of producing electrical polarity was observed by Volta, and about the same time by Erhman.

(133.) This fact suggested to Ritter the idea of his *secondary pile*, which consisted of a series of discs of a single metal alternated with cloth or card, moistened in a liquid by which the metal would not be affected chemically. If such a pile have its extremities put in connection by conducting substances with the poles of an insulated Voltaic pile, it will receive a charge of electricity in a manner similar to the band of wet paper, one half taking a positive and the other a negative charge; and after its connection with the primary pile has been broken, it will retain the charge it has thus received. The secondary pile, while it retains its charge, produces the same physiological and chemical effects as the Voltaic apparatus.

The polarity which the band of wet paper and the secondary pile acquire by their temporary contact with the ends of a Voltaic apparatus, is a consequence of their imperfect conducting power. The electricity of each species appears to force its way through the imperfect conductor till the two opposite currents meet in the centre.

At the time of the discovery of the secondary piles, it was known that a piece of metallic wire, the ends of which had been placed in contact with the poles of a Voltaic pile, does not instantly recover its natural state when its contact with the pile is broken.

(134.) From the experiments of Davy and others, it appeared that if a communication was made between the poles of an insulated pile and two glasses of water, so that the water in the one would be charged with positive, and the other with negative electricity, a metallic wire connecting the two portions of water would evolve oxygen gas at one point, and hydrogen at the other. If, under such circumstances, the connection of the glasses with the pile be suddenly broken, the action of the wire will nevertheless continue for some time, but its effects will be reversed; the point which before disengaged hydrogen will now disengage oxygen, and *vice versâ.* It appears, therefore, that the sudden suspension of the action of the pile has the effect of reversing the direction of the electric current which passes through the wire.*

The continuance of the electric state of a wire which had been used to connect the poles of a pile after its separation from the pile was also demonstrated by Oersted, who showed its effect on the organs of a frog.† The same effect was produced by a wire through which the current of a powerful electrical machine had been transmitted.

(135.) From the chemical effects of the pile, Davy turned his attention to its calorific powers. The means of experimental investigation placed at his disposal were enlarged by the apparatus of the laboratory of the Royal Institution, which was now under his direction. The Voltaic apparatus consisted of a series of 150 pairs of four-inch plates of zinc and copper, and a series of 50 pairs of zinc and silver of the same magnitude. The plates were cemented into four troughs of wood, according to the method proposed by Cruickshank. Another apparatus was provided, consisting of a series of twenty pairs of thirteen-inch plates of zinc and copper.

With the batteries of the smaller plates he repeated some of the experiments on the production of the spark, and the combustion of the metals which had already been made. When the poles consisted of two knobs of brass, the spark which attended the discharge was of dazzling brightness, and one eighth of an inch in apparent diameter. Between pieces of charcoal it had a vivid whiteness, and the charcoal remained red hot for some time after the contact was broken, and threw off bright coruscations. The current passing through steel wire $\frac{1}{170}$th of an inch in diameter, rendered it white hot, and caused it to burn with great splendour. Gold, silver, copper, tin, lead, and zinc were also burnt. Platinum in thin slips was rendered white hot and fused.

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* Histoire de Galvanism de Sue, tom. iii. p. 341.

† Journ. de Opim. de Van-Mons, No. iv. p. 68.

(136.) Fourcroy, Vauquelin, and Thénard had investigated the different effects produced by enlarging the plates of a battery, and by increasing their number. They demonstrated that the power of the apparatus to heat and ignite metallic substances was augmented by enlarging the plates, without increasing their number; but that no increase of power to decompose water, or to produce the shock, ensued. The calorific power, therefore, appeared to depend, *ceteris paribus*, on the magnitude of the plates, while the chemical and physiological power depended on their number.

The battery of thirteen-inch plates was tried successively with pure water, a solution of common salt, and dilute nitric acid. With water its effects were feeble, with the solution of salt they were much more considerable, and were still more energetic with nitric acid. With the last three inches of iron wire, $\frac{1}{170}$th of an inch in diameter, were rendered white hot, and two inches of the same wire were fused. The action of the water, feeble as it was, was ascribed to the air and saline matter it held in solution; and it was judged from analogy that water perfectly purged of air, and free from all saline substances, would have no Voltaic action. A pile of thirty-six pairs of five-inch plates lost its activity in an atmosphere of azote and hydrogen in about two days; and its power was constantly restored by common air, and rendered more intense by oxygen gas.

(137.) When two pieces of well-burnt charcoal, or a piece of charcoal and a metallic wire, are connected with the apparatus and immersed in water, on completing the circuit, gas was abundantly evolved, and the points of the charcoal appeared red hot for some time after the contact was made. Sparks were also produced by means of charcoal points immersed in concentrated nitre and sulphuric acids. When two charcoal points acted in water, the gaseous products consisted of one eighth carbonic acid, one eighth oxygen, and one eighth inflammable gas, apparently hydrogen. The gases produced by a similar process from alcohol, ether, and dilute sulphuric acid, were also a mixture of oxygen and hydrogen. In all these cases it appeared that the gases proceeded chiefly from the decomposition of the water contained in the several solutions.

The effects of the ignition of charcoal in muriatic acid confined over mercury were next tried. The charcoal being kept white hot for nearly two hours, the gas was very little reduced in volume, and the charcoal was not sensibly consumed. When the gas was examined, three fourths of it were absorbed by water, and the remainder was inflammable.*

(138.) Of the theories proposed at this early period of the experimental inquiry to explain chemical decomposition by the Voltaic apparatus, that of GROTTHUS was the earliest and most plausible. To simplify the view of this theory, we shall take as an example of its application the decomposition of water. Each molecule of water being composed of a molecule of oxygen and a molecule of hydrogen, their natural electricities are in equilibrium when not exposed to any disturbing force, each possessing equal quantities of the positive and negative fluids. The electricity of the positive wire acting by induction on the natural electricities of the contiguous molecule of water, attracts the negative and repels the positive fluid. It is further assumed in this theory, that oxygen has a natural attraction for negative, and hydrogen for positive electricity; therefore the positive wire in attracting the negative fluid of the contiguous molecule of water, and repelling its positive fluid, attracts its constituent molecule of oxygen, and repels its molecule of hydrogen. The particle of water, therefore, places itself with its oxygen next the positive wire, and its hydrogen on the opposite side. The positive electricity of the first particle of water thus accumulated on its hydrogen molecule, produces the same action on the succeeding molecule of water as the wire did upon the first molecule; and a similar arrangement of the second molecule of water is effected. This second molecule acts in like manner on the third, and so on. All the particles of water between the positive and negative wires thus assume a polar arrangement, and have their natural electricities decomposed; the negative poles and oxygen molecules looking towards the positive wire, and the positive poles and hydrogen molecules looking towards the negative wire. The attraction of the positive wire now separates the oxygen molecule of the contiguous particle of water from its hydrogen molecule, neutralizes its negative electricity, and either dismisses it in the gaseous form, or combines with it, according to the degree of the affinity of the metal of the wire for oxygen. The hydrogen molecule thus liberated effects in like manner the decomposition of the second particle of water, combining with its oxygen, and thus again forming water and dismissing its hydrogen. The latter acts in the same manner on the next particle of water, and so on. Thus, a series of decompositions and recompositions are supposed to be carried on through the fluid, until the process reaches the particle of water contiguous to the negative wire, and the molecule of hydrogen there disengaged gives up its positive electricity, by which an equal portion of negative electricity proceeding from the wire is neutralized, and the molecule of hydrogen escapes in the gaseous form. It is equally compatible with this theory to suppose the series of decompositions and recompositions to commence at the negative and terminate at the positive wire, or to commence simultaneously at both, and terminate at any intermediate point by the union of the last molecule of oxygen disengaged in the one series with the last molecule of hydrogen disengaged in the other.

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* Davy's Works, vol. ii. p. 214. London, 1839.

Grotthus illustrated this ingenious hypothesis by comparing the supposed phenomena with the mechanical effects produced when a number of elastic balls — ivory balls for example — being suspended, so that their centres shall be in the same straight line, and their surfaces mutually touch, either of the extreme balls of the series being raised and let fall against the adjacent one, the effect is propagated through the series, and the last ball alone recoils in consequence of the impact; and although the action and reaction are suffered by each ball of the series, and each is instrumental in transmitting the effect, no visible change takes place in any ball except the last, and the effect is continued by the alternate action of the extreme balls until the motion is gradually stopped by the resistance of the air, and other external causes.

(139.) The experiments of Davy, which have been already mentioned, were only the prelude to a brilliant series of discoveries, the commencement of which burst upon the scientific world in his Bakerian Lecture for the year 1806. As soon as the splendid results detailed in that paper became known in France, the members of the Institute, rising superior to the feelings of national animosity which at that time unhappily prevailed, unanimously conferred upon its distinguished author the prize which had been established by Napoleon for the best experiments on Voltaic electricity.*

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* It is stated in the Memoirs of Davy by Dr. Paris (p. 168.), that the prize given to Davy was the *annual* medal, worth

The genius, address, and perseverance of him whose vocation is to investigate the laws of nature, are not always confined to the grateful labour of developing truths. The extirpation of error is a task which, while it demands the exercise of equally exalted powers, is never rewarded by that *eclat* which surrounds the discovery of natural harmonies before unobserved and unsuspected. In the commencement of the series of researches now referred to, Davy found it necessary to clear from his path

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3000 francs, which was designed as a reward for the best experiments in electricity which should be made in each year. The same statement is made in a note by the editor in the fifth volume of Davy's Works (p. 56.), edited by his brother Dr. John Davy. — "The minor prize of 3000 francs, founded by Napoleon when first consul, for the most important result in electrical research during each year, was awarded by the Institute to the author for this paper: the principal prize of 60,000 francs, of which the preceding was only the interest, in the opinion of the best judges was rather due to him, as it was proposed to be given 'à celui, qui par ses expériences et ses découvertes, fera à faire à l'electricité et au galvanisme un pas comparable à cela qu'ont fait faire à ces sciences Franklin et Volta.' Thus the writer in the Quarterly Review already referred to remarks, 'It was only questioned by those who were capable of appreciating its importance, whether they acted with strict impartiality in assigning to him the annual interest only, when he appeared to have a fair claim to the principal.'"

On the other hand, the French writers on electricity claim the merit of having given Davy the higher prize: — "Les grandes découvertes," says Becquerel (tom. i. p. 165.), "dont Davy avait enrichi la science électro-chemique, le placaient hors de ligne avec les autres physiciens qui avaient parcouru la même carrière depuis Volta; aussi l'Institut lui decerna-t-il le prix de 60,000 f. qui avait été promis par Napoléon à l'auteur des plus grandes découvertes en électricité, comparables à celle de Volta et de Galvani." Whether Davy received the higher or the lower prize (we believe it was the lower), it is evident that the French scientific authorities *now* think he was entitled to the former.

certain difficulties, and, as he rightly conceived, errors, by which his progress was obstructed.

(140.) When the decomposing powers of the pile were first exhibited, the excitement attending a discovery so unlooked for prevented the details of the experiments from receiving all the attention to which they were entitled. When the circumstances attending the decomposition of water by the Voltaic wires were submitted to closer examination, it was found that indications of the presence of an acid always existed at the pole where oxygen was evolved, and those of an alkali at the other pole. In cases where the water submitted to decomposition might be supposed to hold saline matter in solution, such effects would create no surprise; but they were unequivocally manifested when the water used was distilled, and when there was every reason to think it chemically pure. Mr. Cruickshank explained this, by supposing the acid to be nitrous acid, proceeding from the combination of the azote of the common air held in solution by the water with the oxygen evolved at the positive wire; and the alkali to be ammonia, proceeding from the combination of the same principle with the hydrogen evolved at the negative wire. Desormes maintained that the acid was muriatic; and Brugnatelli that it was an acid *sui generis*, produced by the combination of positive electricity with one of the constituents of water, and called it *electric acid.* Some maintained that the constituents of the acid and alkali came over from the liquid used in the Voltaic apparatus in some undiscovered manner along the wires, and was thus deposited in the water; and others held that it was *generated* out of the elements of the water by Voltaic action. An article was published in the "Philosophical Magazine*," by a Mr. Peel of Cambridge, containing an account of an experiment in which the water that remained, after a large portion had been decomposed by the pile, yielded on evaporation muriate of soda, although the water used in the experiment had been distilled with every precaution necessary to free it from impurities. On inquiry being made at Cambridge, no person corresponding with the name and address of the professed author could be found; and the statement was concluded to be a mere attempt to practise on the credulity of the scientific world, when the surprise was revived by the publication of experiments actually made by Professor Pacchioni† of Pisa, in which the same result was attained as was stated in the pretended Cambridge experiment. Sylvester being led to the same conclusion, ascribed the supposed effects, in common with Pacchioni, to the oxydation of hydrogen, on the one hand in a higher, and on the other in a lower degree than that which forms water.

Such were the confusion and obscurity in which the community of science was involved on the subject of the Voltaic decomposition of water, when the question was taken up by Davy. In common with others, he had observed at an early period the presence of an acid and alkali in water under the process of decomposition; but states, that so early as 1800, he concluded from his experiments that the acid proceeded from the animal and vegetable substances which he employed, and that the alkali arose from the corrosion of the glass vessels in which the experiment was conducted. Similar inferences were made by the Galvanic Society of Paris, by MM. Biot and Thénard, and by Dr. Wollaston; the last of whom removed one of the sources of these disturbing elements by the happy expedient of connecting the positive and negative portions of water by a piece of well-washed asbestos.

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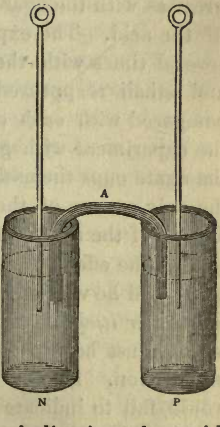
* Vol. xxi. p. 279.

† Vol. xxii. p. 179.

The investigation now undertaken by Davy was commenced by decomposing distilled water in two small cups of agate P N (*fig.* 3.), connected by a piece of white transparent amianthus A. The wires of the Voltaic battery of 160 pairs of four-inch plates were connected with the water, the positive wire being immersed in the cup P, and the negative wire in N. After the process had been continued for forty-eight hours, the water in the cup P was found to redden litmus paper, and turmeric paper was affected by the water in N. It appeared, therefore, and further experiment confirmed the indication, that acid was present in the positive water, and alkali in the negative.

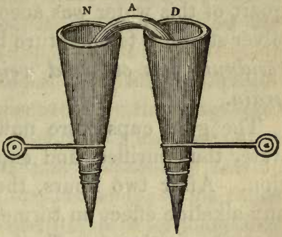
Fig. 3.



This result, after all the precautions which had been taken, was quite unexpected, and, as may be imagined, gave not a little surprise to the experimenter. Still he did not for a moment entertain any of the speculations of the generation of these substances in the water. His next step was to repeat the experiment with glass instead of agate cups, using the *same* quantities of the *same* water, and exposing them for the *same* time to the action of the *same* battery. He argued, that if the cause lay in the water, the effects would be the same; but that if the *cups* had any share in producing them, they might be expected to be different. The result confirmed his anticipation. The alkali was produced in the cup N in quantity twenty times as great as with the agate cups, but there was no trace of the acid. The experiments were then repeated several times with the agate cups, when the acid and alkali reappeared in quantities, which, when compared with each other and with the result of the experiment with glass cups, left no doubt that the agate cups themselves had been the chief if not the only source of the acid, and, in a considerable degree, of the alkali also. Still it was impossible to ascribe the effects altogether to the material of the cups; and he was impressed with the suspicion that the *water itself*, notwithstanding its careful distillation, must have held more or less alkaline matter in solution. It was known that the usual tests would fail to indicate the presence of alkaline impurities when their proportion in water was under a certain limit; and the New River water, which he used, contained animal and vegetable impurities, which might furnish neutral salts capable of being carried over in the process of distillation.

The agate cups were now replaced by two conical cups of pure gold (*fig.* 4.), each containing about twenty-five grains of water. Distilled water in these was exposed to the action of a battery of 100 pairs of six-inch plates. In ten minutes indications of acid and alkali were formed in the cups D and N respectively. The process was continued for fourteen hours, during the whole of which time the acid increased in the cup D. The same increase was not, however, observed in the alkali in the cup N; on the contrary, it reached its maximum state in a short time, and continued without increase afterwards. On heating the cup N, the alkali diminished, but could not be altogether dismissed.

Fig. 4.



These experiments being repeated with similar results, it became apparent that the source of the acid and alkali must exist in the water itself, and must either have arisen from saline matter remaining in solution in the water after distillation, or have been produced by the azote, which exists in minute portions in all water exposed to the air. The latter supposition would not be incompatible with the circumstance of the alkali speedily attaining a maximum, since the continued absorption of azote from the atmosphere by the water would be stopped when the latter would become charged with hydrogen.

The former supposition was adopted, and it was determined to submit the water which had been used in the last experiments to slow re-distillation. A quart of this water was accordingly evaporated in a silver still at a temperature below 140°, and *a saline residuum was obtained weighing seven tenths of a grain.*

The gold cups were now again filled with the water thus purified, and exposed to the Voltaic action. After two hours, the cup N failed to show any alkaline effect on turmeric paper. By very minute observation, its effect on the more delicate test of litmus was perceivable; but this disappeared by the application of heat, and was therefore ascribed to ammonia produced by the combination of the small quantity of azote contained in the water with the nascent hydrogen.

Finally, in order to insulate the results from the disturbing effects of the surrounding atmosphere, the gold cups containing the purified water were placed under the receiver of an air-pump, which was exhausted until the gauge stood at half an inch. Hydrogen gas was then introduced under the receiver, which, mixed with the very minute portion of atmospheric air which had remained, was again withdrawn by the pump. Pure hydrogen gas was now once more introduced around the cups, which, being placed in connection with the Voltaic apparatus, were suffered to remain under its action for twenty-four hours, at the end of which time neither of the portions of the water altered in the slightest degree the tint of litmus.

Thus were dispelled the speculations on the power of electricity to generate new principles in water; and by eliminating the disturbing action of other causes, the decomposing power of the pile upon a binary compound was presented in a manner fitted for theoretical investigation.

(141.) If chance occasionally deprives the philosopher of the merit of discovery by throwing facts under his feet, an ample field for the exercise of his sagacity remains in the due appreciation of the innumerable effects which are incidental to his experimental researches: to seize which as they arise, to pursue them through their consequences, to strip them of the Protean disguises which they borrow from other phenomena with which they become related, to expand them by comparison and generalization into comprehensive natural laws, is the province of the highest powers of philosophical inquiry. Never was this felicitous instinct more conspicuous than in the mind of Davy. No effect, however minute or accidental it might apparently be, presenting itself in his experiments, escaped his vigilance, if it offered the least clue to further discovery. In the course of the experiments just noticed, he found himself embarrassed by the disturbing action of the Voltaic wires on the material of the vessels containing the liquid, which was the immediate object of his attention. One material after another was put aside to get rid of this effect; but the *fact* was not overlooked or forgotten. It proved the germ of a vast discovery.

The negative wire effected a partial decomposition of the glass and agate cups, and brought a portion of their constituents into solution in the water contained in them. Might not a power, which thus subdued affinities so stubborn as those which produce the aggregation of substances so insoluble as agate and glass, be brought to bear on other similar bodies, and perchance resolve into their components substances now considered simple and elementary? As a first trial of the decomposition of insoluble or difficultly soluble bodies, cups were formed of wax, resin, marble, argillaceous schist from Cornwall, serpentine from the Lizard, and graywacké. Being filled with purified water * in the same manner as in the experiments above described, decomposition was in all cases effected and saline matter evolved.

(142.) Pursuing this investigation, he successively decomposed by the same process sulphate of lime, sulphate of strontia, fluate of lime, sulphate of baryta, and other insoluble salts, and in each case obtained the acid in the positive and the base in the negative cup. Certain mineral substances, such as basalt, zeolite, and vitreous lava from Ætna, were examined; and although the saline ingredients in some cases prevailed in extremely minute proportions, their presence was nevertheless distinctly manifested. The soluble compounds, such as sulphate and nitrate of potash, sulphate and phosphate of soda, were easily decomposed, and the results were the same.

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* By purified water in all the following experiments is to be understood water rendered chemically pure by the processes described in p. 144.

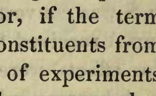
The metallic salts deposited their metallic elements in crystals on the negative wire, round which the oxide was also deposited, while the acid was collected in the positive cup.

These, however, were only the first and least important of the consequences of the idea of extending the principle in virtue of which the Voltaic wire corroded the glass. We shall dismiss this for the present to consider the next series of experiments in these researches, but shall resume the subject.

(143.) From many of his own experiments, and some described by Gautherot, Hisinger, Berzelius, and Ritter, it was apparent that the Voltaic influence was capable not only of decomposing compound bodies, but also of transferring, or, if the term may be permitted, *decanting* their constituents from one vessel to another. The series of experiments which follows next in order in these researches was directed to the examination of the limits of that power, and the effects attending it under conditions not before tried.

When the substance to be decomposed was insoluble, it was formed into a cup, as in the preceding experiments, and water contained in it was exposed to the Voltaic action. Thus, let A, *fig.* 5., be an agate cup, and S a cup made of the substance to be submitted to Voltaic action. Let them each be filled with purified water and connected by asbestos. If A be connected with the positive and S with the negative wire, it was expected that any acid

Fig. 5.



constituent which may be in the substance of which S is formed would pass into A, which would become an acid solution, and appear by the application of the usual tests. If, on the other hand, A be connected with the negative and S with the positive wire, any alkali which may be in the substance of which S is formed was expected to pass into A, and to be manifested there by the common alkaline tests.

In the first case in which his method was tried, the cup S was formed of sulphate of lime. The cup A was connected with the negative and S with the positive wire. With a battery of 100 pair of plates, the water in A was in about four hours converted into a strong solution of lime, and the liquid in S was converted into sulphuric acid. When the cup A received the positive and S the negative wire, the effects were reversed. In that case the water in A became sulphuric acid, and a solution of lime was found in S.

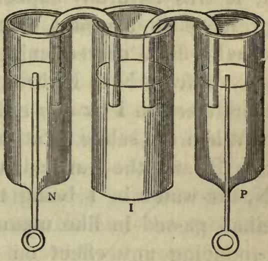
Other saline cups were submitted to the same process with like results; the water in the positive cup always receiving acid, and that in the negative cup alkali.

Two cups of glass were connected with the poles of the battery. One was filled with distilled water, and the other with a saline solution. In every case the salt was decomposed, the base passing into or remaining in the negative, and the acid in the positive cup.

The time required for these transmissions appeared to increase, *ceteris paribus*, as the space through which the decomposed elements were to be transmitted increased.

(144.) To determine whether the action of the metallic wires proceeding from the Voltaic battery was immediately engaged in the production of these decompositions, the next experiments were arranged so that the electric current should be transmitted to the solution to be decomposed through liquid conductors. For this purpose, three cups (P, I, and N, *fig.* 6.) were provided; the extreme ones P and N receiving the positive and negative wires from the battery, and the cup I connected with each of them by amianthus. The cups P and N were filled with purified water, and the solution to be decomposed was put into the intermediate cup I. In every case the acid constituent of the solution was decanted into P, and the alkaline into N. Lest the amianthus siphons should have any mechanical effect on the transference of the solution between the cups, the cups P and N were so filled that the surfaces of the water in them were above that of the solution in I.

Fig. 6.



(145.) As it was now abundantly apparent that the elements of the decomposed substance were drawn from cup N through the interstices of the siphons, it was determined to try how far this decanting power could be carried by breaking the continuity of the siphons, and rendering it impossible for the decomposed element to reach its destination without passing through an intermediate liquid. For this purpose, the three cups being arranged as before, two of them, P and I, were filled with distilled water, the water in I being tinged with litmus; and the negative cup N was filled with a solution of the sulphate of potash. If the energy of the attraction of the positive wire for the acid constituent of the salt were sufficiently strong to cause it to pass from N to P, through the liquid in I, it was naturally expected that, on its route, its presence in I would be rendered manifest by the usual effect of reddening the litmus. The acid passed from N to P through I, but without being manifested in I by any redness of the solution.

When the saline solution was put in the positive cup P, and the purified water in the negative cup N, the water in I being tinged with turmeric, the alkali passed in like manner from P to N without producing any effect on the colour of the liquid in I.

(146.) As the transmission of acid or alkali by means of the electric current through water tinged with vegetable colours was effected without producing any sensible change in these delicate tests of their presence, it was conjectured that, while in this state of transition, or electrical progression, the chemical elements were deprived of their wonted properties, and that therefore they would equally pass through solutions of substances for which, under ordinary circumstances, they exhibit a strong affinity, that affinity being rendered dormant, or counteracted, by the predominating influence of the electrical attraction. To reduce this conjecture to the test of experiment, the water tinged with vegetable colours in the intermediate cup I was replaced by a weak solution of ammonia, purified water was put into the cup P, and a solution of the sulphate of potash in the cup N. The sulphuric acid, attracted by the positive wire, could only reach the cup P by passing through the solution of ammonia. With a battery of 150 pairs, the presence of the acid in P was manifested in five minutes by litmus paper. In half an hour, the solution in P became sour to the taste, and precipitated solution of nitrate of baryta. Thus the sulphuric acid passed through the solution of ammonia in I without producing upon it any chemical change. Solutions of lime, potash, and soda were successively substituted, with similar results.

Muriate of soda and nitrate of potash were successively placed in the cup N, and the muriatic and nitric acids made to pass through concentrated alkaline menstrua in I without any chemical effects.

The neutral salts of lime, potash, soda, ammonia, and magnesia in solution, were successively placed in the cup P, distilled water in N, and sulphuric, nitric, and muriatic acids successively in the intermediate cup I. The alkaline elements of the salts were thus drawn through the acids, and decanted into N, without undergoing any change themselves, or causing any change in the acids.

(147.) Strontia and baryta passed freely by a similar process through muriatic and nitric acids, and reciprocally these acids passed with equal facility through solutions of strontia and baryta. The uniformity of this series of phenomena was, however, broken when it was attempted to transmit the same alkalies through sulphuric acid, or to pass sulphuric acid through them. A new order of effects was here evolved.

A solution of sulphate of potash was placed in the cup N, distilled water in P, and a solution of baryta in I. The sulphate of potash was decomposed as before, and sulphuric acid passed from the negative cup on its route towards the positive wire; but its progress was arrested in the intermediate cup, where it was seized by the baryta and precipitated. It appeared, however, that this obstruction to the progress of the acid was not absolutely complete; for when the process was continued for several days, traces of acid were found in the positive cup. When a solution of strontia was substituted for the baryta in the intermediate cup, the effects were similar.

When the muriate of baryta was put in the positive cup, sulphuric acid in the intermediate cup I, and water in the negative cup N, no alkali passed to the cup N, all being arrested in I, where the sulphate of baryta was manifest, and muriatic acid remained in the cup P.

It appeared, therefore, that the exception to the transmission of the elements of bodies through menstrua for which they have an affinity, includes the cases in which the result of that affinity would be an insoluble compound. The sulphates of strontia and baryta are insoluble in water; and sulphuric acid cannot be transmitted, by the electric current, through strontia or baryta, nor the latter through the former.

The operation of these principles was very beautifully illustrated by the following experiment:—The cups P and N were filled with solution of muriate of soda, and the cup I with solution of sulphate of silver. The cup P was connected with I by a slip of wet turmeric paper, and the cup N was connected with I by a slip of wet litmus paper. When the operation of the battery commenced, the presence of soda in a free state was manifested in the cup N, and muriatic acid in the cup P. The muriatic acid drawn from the cup N, through the litmus paper, was seen to form a dense precipitate in the cup I, and the soda passing through the turmeric paper from the cup P was observed in the cup I forming a more diffused and lighter precipitate. But neither the acid in passing through the litmus paper, nor the alkali in passing through the turmeric paper, produced any change in the colour of these tests.

(148.) When salts having metallic oxides as bases were placed in the cup P, acid solutions being put in I, the oxides passed through the acids; but their progress was much slower than that of the alkalies. When a solution of the green sulphate of iron was placed in P, and muriatic acid in I, the green oxide of iron began to appear in about ten hours on the amianthus connecting N and I; and it took three days to collect any considerable quantity of it in the cup N. The results were similar when solutions of sulphate of copper, nitrate of lead, and nitromuriate of tin were placed in the cup P.

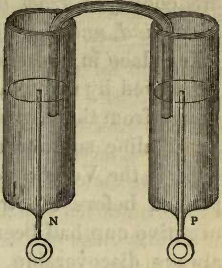
(149.) The transmission of the constituents of salts through solutions of the neutral salts was next tried, and the results were what was anticipated. Saline solutions being placed in N and I, and purified water in P, the alkali of I first began to pass into N; then the alkali of P, after passing through I, reached N, and at the same time the acid of I passed into P. Ultimately the two acids were collected in P, and the two alkalies in N. As an example of this, the cup N was filled with a solution of the muriate of baryta, the cup I with sulphate of potash, and the cup P with pure water. A battery of 150 pairs brought sulphuric acid in five minutes, and muriatic acid in two hours, into P.

When the cup P was filled with a solution of sulphate of potash, I with muriate of baryta, and N with distilled water, the baryta appeared in the water in a few minutes; after an hour the potash became sensible in it.

When the muriate of baryta was in P, the sulphate of potash in I, and water in N, the potash soon appeared in the water; but the baryta was arrested in the intermediate cup by the sulphuric acid, and sulphate of baryta was abundantly precipitated. In like manner, when sulphate of silver was placed in the cup I, muriate of baryta being in N, and water in P, sulphuric acid alone passed into P, and a precipitation took place in I.

(150.) The effects of the electric current on the principles of vegetable and animal substances was next tried. The fresh stalk of a polyanthus leaf was used instead of the siphon of amianthus, to connect the two cups P and N (*fig.* 7.), the cup I being omitted. The cup P was filled with a solution of nitrate of strontia, and the cup N with purified water. The water soon became green, and showed the presence of alkali; and the solution in the cup P indicated the presence of free nitric acid. After ten minutes, the alkaline matter in N being examined proved to be potash and lime, but no strontia had yet arrived in the cup. In half an hour, however, strontia appeared, and in four hours was abundant.

Fig. 7.



A piece of the muscular flesh of beef was used in like manner as a siphon connecting the two cups, P containing a solution of muriate of baryta, and N distilled water. Soda, ammonia, and lime appeared first in the water, and after about an hour and a quarter the baryta began to arrive. Muriatic acid was abundantly liberated in the cup P.

It is nothing more than a general expression of the phenomena which have been just detailed to say, that hydrogen, alkaline matter, metals, and certain metallic oxides, are *attracted* towards the negative, and *repelled* from the positive pole of a Voltaic apparatus; and that oxygen and acid substances are affected with a similar attraction and repulsion in the contrary direction.

(151.) As to the actual process by which the transfer of the element decomposed takes place, either between the positive and negative wires in the solution under decomposition, or through the intermediate solution, no distinct opinion was expressed in the paper now noticed. Davy showed that it is natural to suppose that the repellent and attractive energies are conveyed *from one particle to another of the same kind*, and that locomotion (of these particles) takes place in consequence. He considered this to be proved by many facts. Thus, when an acid was drawn from the negative to the positive cup through an alkaline solution contained in the intermediate cup, if the Voltaic action was for a moment suspended before the transfer of *all* the acid in the negative cup had been effected, traces of acid were always discoverable in the intermediate cup. It appears from this that the series of acid molecules, *while moving* between the ends of the amianthus siphons in the intermediate cup, do not enter into combination with the alkali; but if the motion be for a moment suspended, combination instantly takes place. In this case, therefore, it would not appear that any supposition of transmission by a series of decompositions and recompositions is compatible with the phenomena.

In the cases, however, of the decomposition of water (where the whole menstruum between the decomposing wires is water), and of solution of neutral salts (where also the menstruum is altogether composed of the same solution), he admits that there *may possibly* be a succession of decompositions and recompositions throughout the fluid. He admits also, that the impossibility of transmitting through an acid or alkali any element which forms with it an insoluble compound, although the transmission is perfect when the compound is soluble, supports the hypothesis of a succession of compositions and decompositions taking place in every case. He maintains, that although in some cases insoluble substances are transmitted, the transmission is effected in a manner totally different from that which takes place in the more general case. The insoluble matter was, in these cases, carried over mechanically, either through the interstices of the siphons, or by means of "a thin stratum of pure water, where the solution had been decomposed at the surface by carbonic acid."

It appears from the tenor of the observations in this paper, "on the mode of decomposition and transition," that the mind of the author had not yet arrived at any opinion satisfactory to himself on this subject.

By the experiments of Volta it had been shown that different metals brought into contact were oppositely electrified after separation. Davy found that an acid and a metal being in contact, the former became negative, and the latter positive; but that when an alkali and a metal were in contact, the electrical effects were reversed. As a general fact it appeared, therefore, that positive electricity has a tendency to pass from acids to metals, and from metals to alkalies, and negative electricity to flow in the opposite direction. Different bodies were, therefore, regarded by Davy as having with relation to each other specific *electrical energies*. Acids have a negative and alkalies a positive energy, with relation to metals; while metals have a positive energy with relation to acids, and a negative energy with relation to alkalies.

Various experiments of a delicate kind were made to establish this general principle. To avoid the disturbing effects which would be introduced by chemical action, the substances of each kind selected for experimental examination were in the solid and dry form. When oxalic, succinic, benzoic, or boracic acid, perfectly dry, either in powder or crystals, was touched upon a large surface with a disc of copper, zinc, or tin insulated, the metal became positive, and the acid negative. Phosphoric acid and zinc gave a like result.

Metallic plates being brought in like manner in contact with lime, strontia, magnesia, or soda, became negative, the earths being positive. The attraction of potash for water was too strong to allow that alkali to be submitted to trial. Sulphur became positive after contact with a metallic plate, and the supposed exception to this in the case of lead was removed by showing that the substance rubbed against newly polished lead always became positive.

All these facts went to support the position, that the electrical relation of different substances, as shown by mere contact, was in harmony with the law according to which electricity was developed in the Voltaic apparatus, and with the phenomena of decomposition. To complete the experimental proof of this analogy, it would have been necessary to show that oxygen has a negative and hydrogen a positive electrical energy in relation to the metals. Not being able to accomplish this, recourse was had to the compounds of these substances. Sulphuretted hydrogen in water, used in the Voltaic arrangement of single metallic plates, plays the part of an alkali. To support by a like analogy the negative character of oxygen, he showed that oxymuriatic acid* (chlorine) was more powerfully negative in relation to metal than muriatic acid, even in a higher degree of concentration.

(152.) He assumed, as a principle suggested by analogy and supported by experiment, that *two bodies which have contrary electrical energies in relation to a third body have contrary electrical energies in relation to each other;* that is to say, two bodies, A and B, being successively brought into contact with a third C; if A is found to be positive after separation and B negative, then it follows that if A and B be brought into mutual contact, A will be positive after separation and B negative. Lime and oxalic acid in a dry and solid state, the former being positive and the latter negative in relation to metals, were brought into contact, and the electricity collected after repeated contacts by a condensing electrometer. The lime was found to be positive and the acid negative.

Guided by the analogies suggested by such facts, Davy maintained, as a general principle, that oxygen and acid substances have a negative electrical energy in relation to hydrogen and alkaline substances; and that in the decompositions and changes presented by the effects of electricity, the different bodies naturally possessed of chemical affinities appear to be incapable of entering into combination or of remaining in combination by virtue of these affinities when they are placed in a state of electricity, contrary to the natural relation of their electrical energies. Thus the acids in the positive part of the circuit separate themselves from the alkalies, oxygen from hydrogen, and so on; and metals on the negative side do not unite with oxgyen, and acids do not remain in union with their oxides; and in this way the attractive and repellant agencies seem to be communicated from the metallic surfaces (the poles of the pile) throughout the whole of the menstruum.

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* This substance was then supposed to be a compound.

(153.) In all cases in which bodies combine chemically, they are found to have contrary electrical energies. Examples are numerous. The bodies in the first of the following columns are all negative with respect to those which are opposite to them in the second: —

Oxygen	Zinc.	Gold	Mercury.
Oxygen	Silver.	Metals	Sulphur.
Copper	Zinc.	Acids	Alkalies.

The constituent particles of each of these substances when brought into contact, being naturally in opposite states of electricity, will, according to the common laws of electricity, attract each other. If they be solid bodies, the force of aggregation of these particles, which constitutes the character of their solidity, will resist their separation ; but if the constituent particles be free to move and intermingle among each other, then the attraction due to their proper electricity will take effect, combination will ensue, the conditions of equilibrium of the electrical forces will be satisfied, and all signs of free electricity will cease.

(154.) In support of this hypothesis it is argued, that when, by artificial means, the elements of any compound are invested with electricity contrary to that which naturally belongs to them, such electricity exerting a force contrary to that which produces or maintains, or tends to produce or maintain their combination, that combination, if it exist, is dissolved, and if it tend to be effected, is prevented.

Thus zinc is one of the metals which have the strongest natural tendency to combine with oxgyen. Let it be charged with negative electricity, and its oxydation becomes impossible, because, according to Davy's hypothesis, the positive electricity *naturally* belonging to its molecules is neutralized by the negative electricity *artificially* imparted to it. Again, silver is one of the metals which have the least tendency to unite with oxygen; but let silver be charged with positive electricity, and it oxydates easily. The positive electricity supplied artificially gives increased power to that which the particles possess, so as to augment their attraction for the negative particles of the oxygen.

(155.) The cases of bodies which have contrary electrical energies, either in relation to a third body or in relation to each other, are therefore simple, and easily apprehended. But two bodies may have electrical energies with respect to a third, the same in *kind*, but unequal in *degree*. Thus all acids are negative in relation to metals, but any two of them will be unequally so; and in like manner all alkalies are positive, but unequally positive in relation to metals. Sulphuric acid is *more negative* than muriatic acid in relation to lead, and potash is *more* *positive* than soda in relation to tin. Such bodies compared with each other may have the same or contrary electrical energies, or they may be neutral. Sulphur and the alkalies are positive in relation to the metals, but their electrical energies with respect to each other are contrary.

(156.) The evolution of heat and light, which commonly attends the restoration of electrical equilibrium between two bodies strongly charged with electricity by artificial means, is brought by Davy in further support of his theory. It is well known that heat and light also result from intense chemical action. When the electric current passes through bodies, the electricity being then incomparably more feeble in intensity than that which proceeds from the common machine, heat is evolved without light, and the degree of this heat is, *ceteris paribus*, augmented as the intensity of the electricity is increased. In the same manner in slow chemical combinations there is an increase of temperature without luminous appearance.

(157.) Heat by producing fusion, and liberating the constituent particles of bodies from their natural aggregation, has been regarded as being conducive to their chemical combination. In the theory proposed by Davy it is, moreover, viewed as being otherwise instrumental in giving play to the affinities. That heat is one of the means of exalting the electrical energy of bodies, is apparent from its known effects on glass and tourmaline. But in the experiments now noticed, more distinct and specific evidence is adduced of its direct electric agency. A plate of sulphur was placed on an insulated plate of copper, and the temperature of the bodies being gradually elevated, their electrical state was examined at different stages of the experiment. At 56° the electricity was scarcely sensible to a condensing electrometer; at 100° it affected the gold leaves without the condenser, and increased in a still higher degree as the sulphur approached its point of fusion.

Since heat, therefore, increases the natural electrical energy of the component particles of bodies, it gives them, according to the theory of Davy, an increased tendency to combine chemically, if those energies be contrary. Hence, when a spark, or other sufficient source of heat, is introduced into a mixture of oxygen and hydrogen, it renders the contiguous molecules of oxygen more strongly negative, and those of hydrogen more strongly positive. In virtue of their increased mutual attraction they combine, and in combining heat is evolved, which affecting other contiguous molecules causes further combination, and so on until the combination is complete.

(158.) According to this hypothesis, combination should be rapid, heat and light intense, and the compound neutral in its properties, whenever the electrical energies of the two constituents are strong and perfectly equal. But when they are very unequal, the effects would be less vivid, and the compound would have the acid or alkaline character, according as the energy of the negative or positive constituent is in excess.

The production of water from the combination of oxygen and hydrogen, and the formation of the metallic salts, are adduced as examples of strong and equal energies. Like examples are afforded by the nitrate, sulphate, and chlorate of potash and muriate of lime, which severally, when touched upon a large surface by plates of copper and zinc, gave no electrical signs. Subcarbonate of soda and borax, on the contrary, gave a slight negative charge, and alum and superphosphate of lime a feeble positive charge.

(159.) The next section of this remarkable paper professes to explain the author's views of the "mode of action" of the Voltaic pile. The absence of that perspicuous style of expression which so generally characterizes his writings, in this case justifies the supposition that his own perceptions on the subject of the theory he proposes were not at the time very clear or well defined. It must be recollected that Volta maintained that the source of electricity in the pile was the contact of the dissimilar metals, and that the intervening fluid merely acted the part of a conductor to carry away, in a continued stream, the positive electricity from each zinc surface, and the negative electricity from each copper surface. Fabroni and Crêve, and afterwards Wollaston and others, maintained that the source of the electricity was the chemical action between the zinc and the fluid, and that the intervening copper acted as a conductor to carry away, in a continued stream, the positive electricity from one side of the fluid, and the negative electricity from the other. Davy professed to reconcile these conflicting hypotheses by admitting, with Volta, that the opposite currents were propagated from the surface of contact of the zinc and copper; but that the liquid separating the pairs of plates *did not*, and *could not*, carry forwards the currents, as Volta maintained, by their conducting power, but that they effected that object by the chemical action which took place between them and the zinc. This is our view of the theory proposed by Davy in the paper now referred to; but, as has been already stated, the expressions are not so clear as to remove all doubt of his exact meaning.

Davy uses the term "electrical energy" apparently to express the same phenomenon which Volta called "electro-motive action," and which had been also called "Voltaic action." This term denotes the quantity of electricity evolved upon the two metals on either side of their common surface, according to Volta's theory of contact. The act of conveying forward through the series in each direction the electricity, positive and negative, thus propagated at the common surface, is called by Davy the "restoration of the electrical equilibrium which was disturbed by the electrical energy of the metals." Strictly speaking, there is no *restoration* whatever of electrical equilibrium during the action of the pile. The electric fluids are never in a state of repose. Two currents run in uninterrupted streams in opposite directions. When therefore Davy says that "the chemical changes" produced by the liquid interposed between the metallic elements of the pile are "the causes that tend to restore the equilibrium," he must, as we conceive, be understood to mean that these changes are "the causes by which the electric currents are propagated towards the poles of the pile."

(160.) Having premised these explanations, let us now consider the reasoning and the facts on which this theory of Davy has been based. He denies that the liquid elements of the pile can act as an ordinary conductor of electricity, the term conductor being used in the same sense as when applied to the metals and other solid conductors, because, with regard to electricities of such very low intensity, water (as well as liquids in general) is an insulating body. Besides, there is every reason to believe that, "if the fluid medium were a substance incapable of decomposition (by the metallic elements), the motion of the electricity would cease." When the liquid in a Voltaic arrangement of zinc and copper is a solution of muriate of soda, decomposition ensues. The oxygen and muriatic acid pass through the fluid from the copper towards the zinc, transporting or transported by the negative current; and the hydrogen and soda pass from the zinc towards the copper, transporting or transported by the positive current. Whether the author considered that the transfer of the electricity is effected by the locomotion of the decomposed elements through the fluid, or by a series of decompositions and recompositions, in which there is no motion of translation imparted to any of the elements resulting from the decomposition, and in which the electricities themselves are not transferred through the fluid, but rendered alternately free and latent as the successive decompositions and recompositions are effected, does not appear from the developments contained in this paper.

A pile of twenty-four pairs, in which the connecting fluid was water free from air, had no Voltaic power. To determine whether another liquid with superior conducting power, but still incapable of chemical action, would be affected, concentrated sulphuric acid was tried. No permanent current was produced. Solutions of neutral salts render the pile active at first; but when, by continued decomposition, the solution in contact with the zinc becomes acid, and that in contact with the copper alkali, the action ceases. Dilute acids being themselves easily decomposed, and promoting the decomposition of the water, dissolving the oxide of zinc as fast as it is formed, and evolving gases only on the copper side, are the most powerful and durable fluid elements for a pile. All these facts supply converging evidence upon the position that chemical action is essential to the vitality of the Voltaic apparatus.

Against the hypothesis that chemical change is the *primary* source of the action of the pile, it is contended that in a combination of zinc and copper plates with dilute *nitrous* acid, the side of the zinc exposed to the acid is positive; but in a Voltaic combination of zinc water and dilute *nitric* acid, the side of the zinc exposed to the acid is negative. The chemical action of the acid on the zinc being in both cases the same, it is argued that if the electric currents originated at the common surface of the zinc and acid, which they would do if chemical change were their primary source, the direction of the currents would be the same, instead of being contrary in the two cases.

As a further argument against the chemical theory of the pile, Davy maintained that in mere cases of chemical change, electricity is never exhibited; and endeavoured to support this position by the examples of iron burned in oxygen, the deflagration of nitre and charcoal, the combination of solid potash and sulphuric acid, and other chemical actions. Subsequent investigation, however, has shown that this principle is not tenable, and that chemical change *is* attended with the evolution of electricity.

(161.) With Davy, as with Franklin, *application* ever trod closely on the heels of *discovery*. The same memoir which disclosed the brilliant series of discoveries of which we have here attempted to give a brief analysis, also indicated the vast applications of which they were susceptible, in the further investigation of the laws of nature, and in arts conducive to the economy of life. The detection of acid and alkaline matter in mineral, animal, and vegetable substances, and their separation from them, was sufficiently obvious. A piece of muscular fibre, through which the electric current was transmitted for five days, was rendered dry and hard. Potash, soda, ammonia, lime, and oxide of iron were carried from it by the negative current; and the three mineral acids, with phosphoric acid, passed off with the positive current. From a laurel leaf the negative current carried green colouring matter, resin, alkali, and lime, and the positive current took vegetable prussic acid. Mint gave potash and lime with the negative, and an acid matter with the positive current. The flesh of the living hand, carefully washed in pure water, gave a mixture of muriatic, sulphuric, and phosphoric acids with the positive current, and fixed alkaline matter with the negative current. This fact accounts for the acid and alkaline tastes first observed by Sulzer given by metals in contact.

By converting the processes, the Voltaic currents may be made the means of introducing acids and alkaline, or metallic principles, into the animal and vegetable system. This idea has since been realized in medical practice by some physicians.

(162.) In the experiments hitherto made, the acids and alkalies themselves were not decomposed. The history of scientific discovery affords no more remarkable example of that instinctive foresight which enables the philosopher to suspect the direction in which truth lies, and prompts him in the selection of subjects of inquiry, than is apparent in comparing Davy's present guesses with the result of his subsequent researches. "These facts," says he, "induce us to hope that this new mode of analysis may lead to the discovery of the *true* elements of bodies, if the materials acted on be employed in a certain state of concentration, and the electricity be sufficiently exalted. For if chemical union be of the nature which I have ventured to suppose, however strong the natural electrical energies of the elements of bodies may be, there is yet every probability of a limit to their strength: whereas the powers of our artificial instruments seem capable of indefinite increase."

How soon he led the way towards the realization of this magnificent conjecture will presently appear.

(163.) Sudden and violent derangements of the electrical equilibrium of the elements of our system are manifested in other cases besides the *glaring instances* offered by atmospheric phenomena. The electrical appearances which precede and attend earthquakes and volcanic eruptions admit of easy explanation on the electro-chemical theory. The slow and gradual changes observed by the geologist are indications of the more tranquil and incessant operations of electrical agency. Where strata of pyrites and coalblende occur; where the pure metals or the sulphurets are found in contact with each other, or with any conducting substances; and where different strata contain different saline menstrua, electricity must be evolved, and by its agency mineral formations would probably be influenced or produced.

(164.) These views, which have been recently confirmed by the observations of Mr. Fox on the electrical condition of the metallic veins in Cornwall, were illustrated by experiment. A mixed solution of muriates of iron, copper, tin, and cobalt, was placed in the positive cup P, and distilled water in the negative cup N, the cups being connected by asbestos. The four oxides passed through the asbestos to the cup N; a yellow metallic crust was formed on the negative wire, round the base of which the oxides collected in a mixed state. In another experiment the carbonate of copper was diffused in minute subdivision through water, and a negative wire placed in a small perforated cube of zeolite in the liquid. Green crystals collected upon the cube and adhered to it, the particles being incapable of penetrating it. By the multiplication of such instances, Davy conceived that the electrical power of decomposition and transference would afford a satisfactory explanation of some of the principal facts in geology, and his anticipations have since been to a considerable extent realized by the researches of Becquerel and others. "Natural electricity," says Davy in the conclusion of this memorable paper, "has hitherto been little investigated, except in the case of its evident and powerful concentration in the atmosphere. Its slow and silent operations in every part of the surface will probably be found more immediately and importantly connected with the order and economy of nature; and investigation on this subject can hardly fail to enlighten our philosophical systems of the earth, and may possibly place new powers within our reach."*

(165.) His theoretical ideas on the application of electrical decomposition to the solution of the phenomena of geology were seized with ardour by GUYTON MORVEAU. That eminent chemist, like Davy, endeavoured to exhibit on a small scale, by direct experiments, the processes which are continually going on in the crust of the earth. The native oxide of antimony he regarded as an example of slow transition from the state of a sulphuret to that of a pure oxide, by means of the decomposition of water by subterranean electricity. By careful examination of a specimen of this mineral, he observed that it still retained the structure of the crystallized sulphuret of antimony, and even preserved partially its metallic lustre, and inferred that a slow Voltaic action had changed its composition without disturbing the arrangement of its constituent parts. To support those ideas suggested to him in Davy's celebrated paper by direct experiment, he submitted a piece of sulphuret of antimony to the action of a powerful Voltaic apparatus. An odour of sulphuretted hydrogen was soon perceivable; the liquid assumed a yellow colour, and the sulphuret appeared of a darker tint and iridescent, indicating incipient decomposition. The negative plate became black, and the positive one was coated with a light yellow incrustation, which proved to be the oxide of antimony. Thus it appeared that the sulphuret of antimony was capable of being transferred immediately into the oxide by the mere operation of the Voltaic forces. Other native sulphurets were tried in like manner, and gave similar results.*

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* Philosophical Transactions, 1807.

(166.) During the twelve months next succeeding the date of the memoir above noticed, Davy devoted his labours, and directed all the powers of his genius, to the development of the consequences of the theoretical principles which he had propounded, and to the realization of the ideas he had ventured to throw out respecting the resolution of natural substances, before regarded as simple, into their constituents. Never before did Theory more surely lead to Discovery; never was the prophetic instinct of a philosopher more speedily or more magnificently satisfied. His foreknowledge of the facts to be disclosed and the instruments for their disclosure, of the end to be attained and the means of attaining it, of the route to be followed and the goal to be reached, was distinctly expressed; and with the confidence inspired by clear perceptions and conscious power, he immediately advanced in the course he described, and attained the end he foresaw. The resolution of the alkalies and earths into their elements was the splendid result of his labours during the year 1807, and was consigned to the Bakerian Lecture read before the Royal Society on the 19th of November in that year.

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* Annales de Chimie, tom. liii. p. 113.

(167.) His first efforts were directed to potash, which was submitted in a state of solution to the electric current. The water only was decomposed, the alkali refusing to yield. In its dry state it would not transmit the current. In order to give it a conducting power, and at the same time exclude water, on which by preference the current appeared to act, the alkali was now placed in a platinum spoon, and exposed to the flame of a lamp directed upon it by a blast of oxygen. When reduced to the fluid state by such means, the potash transmitted the Voltaic current. When the metal of the spoon was positive, and the point of a platinum wire inserted in the fluid alkali negative, combustion attended by intense splendour was exhibited at the wire, and a column of flame arose from the point of contact of the wire with the alkali. When the spoon was negative, and the wire positive, a vivid light appeared on the former; aeriform globules rose through the liquid potash, which inflamed as soon as they escaped into the air.

It was conjectured that the constituent of the potash, attracted by the negative pole, was the matter which in these cases escaped in bubbles; and that its affinity for oxygen was so strong, that the moment it came in contact with the atmosphere it recombined with oxygen and produced combustion. The question, therefore, now was, how to arrest that element, and submit it to examination?

As the liquefaction of the alkali by heat appeared to entail, as a consequence, the immediate recombination of its separated constituent, it was now attempted to give the necessary conducting power to the potash, by allowing it to imbibe from the atmosphere as much moisture as would give a conducting power to its surface. The alkali in this state was placed on a platinum disc, which was connected with the negative pole, while a wire connected with the positive pole was applied to its upper surface. *At the upper surface there was a disengagement of gas; at the lower surface small metallic globules appeared, like mercury, in their visible character.* Some of these burnt by contact with the air. Others had their metallic lustre tarnished, and finally covered with a white film, which defended them from the atmosphere, and preserved them in their metallic state.

The gas disengaged at the positive wire was oxygen, and the metal deposited was the base of the alkali, afterwards called POTASSIUM.

(168.) Soda, when submitted to a like process, gave a similar result, and the metal educed from it was that which is now called SODIUM.

This capital discovery was made in October, 1807.

Potassium was discovered on the 6th of that month, and sodium a few days after.

Sensitive friends of the great British chemist have been moved to vindicate the glory of this discovery from those who would tarnish it, by ascribing to the accidental possession of the laboratory and apparatus of the Royal Institution of Great Britain a share in producing it. These generous survivors may tranquillize their fears. Possibly such vindication may be called for by a portion of the present generation having pretensions sufficient to raise them to the level of envy, but wanting those better qualities which would elevate them above it. Certainly no such apology will be needful with posterity.

(169.) The strong affinities of these new metals for one or other of the constituents of almost every body with which they were brought in contact, and of every menstruum or atmosphere with which they could be surrounded, was very embarrassing, and rendered the examination of their physical properties extremely difficult. It was found most convenient either to preserve them in a tube protected from the contact of the air above recently distilled naphtha, or to allow them to combine with mercury so as to form an amalgam, and in that state to preserve them, separating them by heat when the pure metal was required.

(170.) The analogy suggested by the decomposition of the fixed alkalies naturally led to a like inquiry with respect to the earths which enjoy with the former common properties, and those which seemed most analogous to the alkalies. Baryta, strontia, lime, and magnesia, were tried by like methods, but without any satisfactory result. Being slightly moistened at their surfaces, they were exposed to the electric current transmitted by iron wire under naphtha. At the negative pole they assumed a darker colour, and small particles appeared there showing metallic lustre, and which gradually whitened by exposure to air. In the experiments on potassium it was found that when a mixture of potash and the oxide of mercury, tin, or lead, was exposed to the Voltaic current, decomposition ensued, and an amalgam of potassium was produced. The same method was accordingly tried with the alkaline earths. Mixtures of these substances with oxides of tin, lead, silver, and mercury, were exposed to the current. In these cases, a small quantity of a substance having the whiteness of silver was deposited at the negative pole, which was found to be an amalgam. Still the results were not conclusive or satisfactory.

(171.) The labours of Davy had attained thi point, when, in June, 1808, he received a letter from M. Berzelius, informing him that, assisted by Dr. Pontin, that chemist had succeeded in decomposing baryta and lime, by exposing them in contact with mercury to the current. Davy immediately repeated the experiment, and obtained the amalgam of the metallic base of baryta at the negative pole. This was accomplished by a battery of 500 pairs, weakly charged, acting on a surface of slightly moistened baryta through the medium of a globule of mercury. The mercury gradually became less fluid, and after a few minutes was found covered with a white film of baryta; and when the amalgam was thrown into water, the latter was decomposed, hydrogen was dismissed, mercury precipitated, and a solution of baryta formed. A like process gave a similar result with lime.

(172.) Having thus verified the results obtained by Berzelius, Davy extended the same method to strontia and magnesia. The former readily yielded; the latter was more intractable. By continuing the process, however, for a longer time, and keeping the earth continually moist, at last a combination of the basis with mercury was obtained, which slowly produced magnesia by absorption of oxygen from the air, or by decomposing water.

Thus were discovered BARIUM, STRONTIUM, CALCIUM, and MAGNESIUM, as an immediate consequence of the first great step made in this course of investigation by the discovery of potassium and sodium.

(173.) The next group of earths brought to trial consisted of alumina, silica, zirconia, and glucinia, which proved more refractory than any of the former. Driven in search of other methods of experimenting, he considered minutely their qualities in relation to other bodies, with a view to the discovery of analogies by which his researches might be conducted. From the absence of any tendency in alumina and silica to yield to the attraction of the electric current in the direction of either pole, he inferred the probability of their partaking of the nature of neutro-saline substances, and attempted their decomposition by processes suggested by that supposition. Failing in these, and observing that alumina and silica have both a strong affinity for potash and soda, and considering that such affinity could not proceed from the oxygen which might be one of their constituents, he inferred that it must be a quality of their metallic bases, and that it would, in that case, be probable that, if mixed with soda or potash, and exposed to the electric current, the base might be made to separate, and to attach itself to the base of the alkali. A mixture of silica and potash, in the proportion of one to six, was accordingly put in a platinum crucible, and reduced to a fluid state over a charcoal fire. The crucible was put in connection with the positive pole of a battery of five hundred pairs, and a rod of platinum connected with the negative pole was brought in contact with the alkaline menstruum. The moment the end of the negative rod touched the liquid, globules rose through it to the surface, on which they swam about in a state of brilliant combustion. When the mixture cooled, the platinum bar was removed, and the alkali and silex which adhered to it detached; there remained upon it brilliant metallic scales, which, immediately on exposure, became covered with a white crust, and some of which burnt spontaneously. Being plunged in water, the end of the platinum produced effervescence, and an alkaline solution was formed, which, upon examination, was proved to contain silica. The same process applied to alumina gave a like result.

It was now determined to try the effect of the Voltaic current upon the earths, in contact with potassium itself. An amalgam of potassium, in contact with silica, was negatively electrified under naphtha. After being acted on for an hour, the amalgam was made to decompose water, and the alkali thus obtained was neutralized by acetous acid. A white precipitate was obtained having all the characters of silica.

The same process was applied, with the same results, to alumina, glucinia, and zirconia. It was inferred, therefore, that these earths were oxides of metals, to which respectively the names of SILICIUM, ALUMINIUM, GLUCINIUM, and ZIRCONIUM were given.

(174.) Having established, by direct experiments, the fact that so many of the alkaline and earthy substances were oxides with metallic bases, it was consistent with sound physical logic to assume, as a general law, that "*the alkalies and earths are oxides of metals.*"

(175.) The question, how far the volatile alkali, Ammonia, was to be regarded in relation to such a law, naturally presented itself. Without reference to this analogy, or offering any hypothesis to explain the fact, SEEBECK had already shown that an amalgam could be obtained by the action of ammonia on mercury. This fact was reproduced by Berzelius and Pontin, and communicated by them, with various circumstances attending it, to Davy. Berzelius maintained that ammonia came within the scope of the general law, and that an idea which had been previously thrown out by Davy was justified by the phenomena which showed that ammonia was a *binary metallic base.* This question was then taken up by Davy, and the experiments of Berzelius repeated, but without arriving at any certain or clear result. Gay-Lussac and Thénard opposed the views of Davy and Berzelius; and a contest arose, for which, as it has little connexion with the progress of electrical science, we shall merely refer to the scientific periodical works in which it was carried on.*

(176.) It has been already observed, that the character of Davy's mind was to pass directly from discovery to application. In the same memoir which contained the announcement of the subjugation of the alkalies and earths by the powers of the pile, is found his brilliant hypothesis to explain the phenomena of volcanoes and aerolites. The metallic bases of the alkalies and earths cannot exist at the surface of the earth in their simple or uncombined form, nor even alloyed with the more perfect metals, because of the intensity of their affinity for oxygen. But the same cause does not prevent their existence in the interior parts of the globe. Let the possibility of the existence of potassium, sodium, calcium, or any other metals of the same class in the inferior strata of the earth, either in a separate state or in combination with other metallic substances, be admitted; and it is only necessary to imagine their occasional exposure to the action of air or water, to obtain a satisfactory solution for volcanic eruptions. These highly combustible metallic principles, combining with oxygen, attended by violent combustion, are ejected from the bowels of the earth, and form the craters of volcanoes, the combination being an earthy matter exhibited after its ejection as lava. The formation of aerolites might proceed from the same causes, their luminous appearance and detonation being produced by the combustion attending the combination of the metals with oxygen as they enter the atmosphere.

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* Annales de Chimie, tom. lxxii. p. 193., lxxv. 256—291; Biblioth. Brit., June, 1809, p. 122.

With a view to test the validity of these ingenious hypotheses, Davy investigated carefully the phenomena of active volcanoes; and, not finding them to be in sufficient accordance with these, he relinquished his theory, without any of that regret which attends the failure of a favourite hypothesis, when the discovery of truth is an object secondary to the attainment of personal distinction.

(177.) The powers of decomposition and transfer by Voltaic electricity, so strikingly exhibited in the researches of Davy, directed the attention of physiologists and others once more to the investigation of the agency of electricity in the vegetable and animal economy. The experiments which had been made to show that the alkaline and earthy elements found in organized vegetable substances were evolved, by the process of vegetation, from air and water, had always been inconclusive and unsatisfactory; and Davy's experiments, in which it was shown that even in water carefully distilled there is still held in solution a portion of saline or metallic matter, together with the known fact, that air almost always holds in mechanical suspension solid matter of various kinds, finally overturned such hypotheses. All the substances developed in organized nature may be produced, by ordinary processes, from combination of known constituents. The compounds of iron, alkalies, and earthy bodies with mineral acids, abound in vegetable soil. The decomposition of basaltic, granitic, and other rocks affords a constant supply of earthy, alkaline, and ferruginous matter to the superficial part of the earth. In the seeds of all plants which have been examined, neutro-saline compounds, containing potash, soda, or iron, have been found. It is easy to imagine that these principles pass from vegetables to animals.

(178.) The same analogies suggested to Dr. Wollaston the idea, that something like the decomposing and transmitting powers of the pile is the agent to which the animal secretions are due, especially as the existence of such agency in a considerable degree of intensity, in certain animals, was proved by the effects of the torpedo and Gymnotus electricus; and he considered that the universal prevalence of the same power, lower only in degree in other animals, was rendered highly probable by the extreme suddenness with which the nervous influence is propagated from one part of the living system to another. Although the electric power of decomposition and transfer has been experimentally demonstrated only in cases of comparatively high intensity of action, yet analogy countenanced the idea that very feeble electric energies would produce like effects more slowly, in proportion to their weakness. To illustrate this by immediate experiment, he tied a piece of clean bladder over one end of a glass tube three quarters of an inch in diameter, and two inches long, and filled it with water holding $\frac{1}{240}$ of its weight of salt in solution. Placing it on a shilling, he connected the silver with the surface of the water by a wire of zinc, and found that alkali was transmitted through the bladder to the silver by the attraction of the negative electricity. Decisive indications of this were obtained in five minutes. The efficacy of a power so feeble confirms the conjecture that similar agents may be instrumental in various animal secretions. The blood, which is alkaline, supplies the bladder with matter in which acid is strongly manifested; while an excess of alkali, above that contained in the blood, is manifested in bile. These effects would be explained by admitting a permanent state of positive electricity in the kidneys, and negative electricity in the liver. The coincidence of this view with the guesses of Napoleon, already mentioned (117.), is curious and interesting.*

(179.) The last great discovery of Davy directed the attention of the philosophers of the Continent to the same field of inquiry; and, much as had been expected from the powers of the pile when its illustrious inventor expounded its nature and properties to the assembled members of the Institute in 1801, it was now, from day to day, rendered more evident that these powers were inadequately estimated, and imperfectly understood, and that it was still destined to enrich every branch of physical science by the development of new and unlooked-for phenomena. Napoleon, in the magnificent spirit with which his encouragement of the sciences was always manifested, had presented to the laboratory of the Polytechnic School a Voltaic apparatus of immense magnitude and power. With this instrument MM. Gay-Lussac and Thênard undertook an experimental investigation of the powers of the pile, with the view of determining more especially the influence which the number of the metallic elements, and the nature of the liquid used to charge the pile, have on its chemical action. Assuming, as a modulus of the chemical energy of the pile, the quantity of gas evolved in the process of decomposition in a given time, they arrived at the following conclusions: — 1. The decomposing energy depends conjointly on the conducting power of the liquid under decomposition, and on the nature of that which is used to charge the pile. 2. It is greater when the pile is charged with a mixture of acid and salt, than with salt alone. 3. The chemical effects are proportional to the force of the acids by which it is put in action: and, 4. They do not augment in the same ratio as the number of pairs of plates, but very nearly in the ratio of the cube root of that number.

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* See Philosophical Magazine, vol. xxxiii. p. 1088.

(180.) That part of the electro-chemical theory of Davy in which the negative character natural to certain physical elements, and the positive to others, is assumed, was implicitly, if not expressly, included in the hypothesis of Grotthus. Without such a supposition, the series of decompositions and recompositions imagined by that philosopher could scarcely be admitted. The probable connexion of chemical attractions with electric forces had been also conjectured by Hube in his *Traité de Physique*, and Ritter obscurely expressed some ideas of the same kind. Immediately before the commencement of Davy's researches, Oersted, since so celebrated for his discoveries in electro-magnetism, promulgated a theory *, in which he maintained that all the phenomena of chemistry might be regarded as the result of two general forces common to all matter, and that the same forces produced those effects which were rendered sensible in electric attractions and repulsions. This work, however, was exclusively of a speculative kind, unsupported by any experiments which could give force or validity to the theory it proposed.

The electro-chemical theory of Davy was the first which had ever professed to be based on clear and well-ascertained facts. It was laid down as a fundamental principle in this theory, that when two bodies, the particles of which are in opposite electrical states, and sufficiently exalted to enable their electric attraction to overcome the force of aggregation of their particles, are brought into contact, they will unite, and heat and light will be developed by the combination of the two electric fluids. When the combination is effected, all signs of electricity cease, as would necessarily ensue from the union of the two fluids, but by what power the aggregation of the new compound was maintained was not explained.

(181.) Berzelius and Ampère, who, of all the philosophers of the Continent, evinced most justice and candour in their appreciation of Davy's merit, took up

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* Recherches sur l'Identité des Forces Chimiques et Electriques. Traduit de l'Allemand. 1813.

the electro-chemical theory, which was not pursued through its consequences by its author, owing probably to the natural disposition of his mind to investigate new facts rather than discuss the merits of hypotheses. Berzelius assumed that the constituent atoms of bodies were not only naturally electrical, as Davy had maintained, but that they possessed electric polarity, and that the intensities of their poles are unequal. He investigated, in the first place, the two questions, How electricity exists in bodies? and, How it is that some bodies are naturally negative, and others sometimes positive and sometimes negative?

(182.) A body never becomes electric, without manifesting the two opposite electric principles, either in different parts of it, or in the sphere of its action; when the two electricities appear separately in a continuous body, they are always found on opposite sides. The tourmaline and some other crystals offer an example of this. But, since the parts of a body possess the same properties as the body itself, it is necessary to admit that bodies are composed of atoms, each of which has an electric polarity, and its poles have unequal intensities. On this polarity depend the chemical phenomena, and its unequal intensity is the cause of the different force exercised by their affinities. Bodies are accordingly electro-positive or electro-negative in combining, according as the influence of the one or other of their atomic poles predominates.

The degree of polarity in this theory is influenced by the temperature. Thus many substances at common temperatures manifest but feeble electric polarity, which, at a red heat, show a very strong one.

No combination can be effected unless the polarized molecules of one or both of the combining bodies have free mobility amongst each other, each being at liberty to turn on its own centre in any direction, so that the particles may present towards each other their contrary poles in obedience to their electric attraction. This condition renders it necessary that one or both of the combining bodies be in the fluid state.

The vulnerable point of this theory was found in the phenomena of aggregation. In what manner can the electric forces which it assumes produce the hardness, brittleness, ductility, and tenacity of different species of solids; the viscidity of liquids; or the elasticity of gases?

Berzelius admits that these effects are not explicable by this hypothesis. M. Ampère attempted to solve this question *, by assuming that the atoms of bodies possessing each its proper electricity, in virtue of which they are united in combinations in the same manner as two leaves of paper oppositely electrified adhere to each other, also act by their electricity on the electricity of the medium in which they exist, attracting the fluid of the contrary name, and repelling the fluid of the same name. The atoms are therefore considered as strictly analogous to the Leyden jar; the internal charge representing the natural electricity of the atom, and the external that which is drawn from the surrounding

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* Journal de Physique, 1821.

medium. If a combination is formed between an electro-positive and an electro-negative body, a discharge takes place; the atoms dismiss their external charge, and rush into union in virtue of the reciprocal attraction of their opposite natural electricities. The atmospheres of the atoms, as well as the atoms themselves, are combined; but, as the atoms cannot emerge from them, their electricities act on those of their atmospheres, exerting attractions and repulsions, so as to produce electrical phenomena the reverse of those which attended their combination.

(183.) The zinc plates of a Voltaic apparatus, being subject to continual oxydation, are at length so reduced in thickness, as to render it necessary to replace them by new ones. This gradual wear of the pile by use rendered it desirable to seek for means of constructing a pile composed of solid elements only; a project, however, which could only be entertained by those who conceived that chemical action was merely incidental, and not essential, to the development of Voltaic electricity. Although the high probability, if not the certainty, that chemical action is indispensable, must render abortive all attempts at the discovery of a *dry pile*, such researches have nevertheless been attended with some advantage. In 1803, MM. Hachette and Desormes substituted starch for the liquid in the common pile; and, in 1809, De Luc invented a pile apparently free from any liquid element. This apparatus consisted of a column formed of alternate discs of zinc and paper gilt on one side, the gilt sides of the paper discs being all turned in one direction. This was in reality not a *dry pile;* the paper imbibed and retained moisture enough to give a feeble activity to the apparatus.

(184.) De Luc's pile was improved by Zamboni in 1812. He rejected the discs of zinc, and composed the pile of discs of paper only, one surface being tinned, and the other coated thinly with the peroxide of manganese, brushed with a mixture of flour and milk; or gilt or silver paper may be used, the metallic surface being wetted with a saturated solution of the sulphate of zinc, on which, when dry, the peroxide of maganese in powder may be spread. Several leaves of paper thus prepared are placed one upon the other, and cut into the required form by a circular cutter. As many discs are thus formed by one operation as there are leaves of paper superposed; and these being afterwards laid one upon the other, the pile is formed. This pile is usually placed in a hollow cylinder of the same internal diameter. The paper discs are forced into close contact by pressure produced by screws.

In these, as in the pile of De Luc, the humidity of the paper is the source of Voltaic power. Although, by the aid of a condenser, the electricity evolved in these piles may be rendered sensible, and sparks may even be obtained, the power is incomparably more feeble than that of the common pile, even in its most inefficient state. It is found that by increasing beyond a certain limit the number of discs composing these, their power is diminished. Their effects have been generally limited to those produced on the condenser; but, by diminishing considerably the number of discs, M. Pelletier has succeeded in decomposing water by these instruments. Their action, however, ceases after the lapse of a certain period, when the paper has lost all its humidity.

(185.) The only uses to which dry piles have been hitherto applied are — 1. To produce a continued motion, by an electrical pendulum suspended between the contrary poles of two such piles placed side by side, so that the positive pole of one and the negative pole of the other shall be at the summit. This motion will be continued as long as sufficient moisture is retained by the elements of the piles to sustain their activity; but it will not be regular, since the development of electricity will be affected by variable atmospheric causes. 2. In condensing electrometers, to detect the presence of very small quantities of electricity on the inferior plate of the condenser.*

(186.) We shall here conclude this brief sketch of the progress of Voltaic electricity, regarding the phenomena and natural laws which have been more recently developed as belonging to the topics of present investigation rather than to the history of the past, and reserving them, therefore, for their suitable place in the work we have undertaken.

III. MAGNETISM.

(187.) The substances endowed with magnetism exhibit that property by three distinct effects: —

1. They attract iron and all ferruginous matter.

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* Becquerel, Traité de l'Electricité, tom. i. p. 166.

2. Two bodies endowed with the property of magnetism will attract each other at one part of their dimensions, and repel each other at another part. These contrary effects, belonging to opposite sides or ends, are called MAGNETIC POLARITY.

(188.) 3. When a magnet is placed on a vertical axis through its centre of gravity, on which it is free to revolve, the axis being between its poles, it will oscillate on each side of a certain determinate position, in which it will at length come to rest. When in this position, a vertical plane passing through the axis and the poles will be nearly, but not exactly, coincident with the plane of the meridian of the place in which the magnet is situate. For all magnets similarly supported, in the same situation, these planes will be parallel. This plane is called the MAGNETIC MERIDIAN. The angle which the magnetic meridian makes with the terrestrial meridian is called the VARIATION of the magnet.

(189.) 4. If a magnet be placed on a horizontal axis passing through its centre of gravity at right angles to the magnetic meridian and between its poles, it will oscillate on each side of a certain determinate position, in which it will at length come to rest. When in this position, a plane passing through the axis and the poles of the magnet will not be horizontal, but will make a certain angle with a horizontal plane through the axis. This angle is called the DIP of the magnet.

The power of the magnet, when placed on a vertical axis, to fix itself in the magnetic meridian of any place to which it may be transported, is called its DIRECTIVE POWER, and is the principle on which its application to navigation depends.

(190.) The attractive power of the magnet for iron was the property which was first observed. This property was known to the ancients, who gave to the natural magnet (an oxide of iron) the name *Magnes* (μαγνης); derived, as is supposed, from Magnesia, a district of Lydia, in which the natural magnet was found in greatest abundance. It was also called *Lapis Heracleus,* from Heraclea, a city of Lydia. From some passages in ancient authors, it would seem that the force of magnetic attraction in very high degrees of intensity was then generally known. Pliny relates that Dinochares proposed to Ptolemy Philadelphus to erect a temple at Alexandria, the dome of which should be built of loadstone, so as to sustain in the air an iron statue of Arsinoë. Saint Augustine also alludes to a statue thus suspended in the air in the middle of the temple of Serapis, at Alexandria.

(191.) The polarity and directive powers of the magnet were discoveries of a much more recent date. The application of the magnetic needle to navigation must have immediately succeeded the first knowledge of its directive power, but the discoverer is unknown; and even the century which was honoured by the invention of this most beautiful application of science to the uses of man is uncertain. It is stated, in the account of the Chinese empire by Du Halde, that the directive power of the magnet was used in that part of the globe, for the purpose of land journeys, more than a thousand years before the birth of Christ. If such were the case, it is difficult to imagine that its use for sea voyages should have failed to spread itself westward until two thousand years later. But, besides this, there are other reasons why little credit is to be given to the accounts which ascribe this invention to the Chinese.*

(192.) The earliest work in which the use of the mariner's compass is distinctly mentioned is a manuscript poem of the twelfth century, preserved in the Royal Library at Paris, the authorship of which is attributed to Guiot de Provins. Guiot was at the court of the emperor Frederic Barbarossa, held at Mentz, in the year 1181.

Hansteen, in his work on the "Magnetism of the Earth," quotes an Icelandic historian, to show that the directive power of the loadstone was known a century antecedent to the date of this poem. That annalist, relating a voyage made in those seas, says incidentally, that "In those times, seamen had no loadstone in the northern countries." It appears that this writer, *Arc Frode*, was born about the year 1068, and therefore probably published his account early in the twelfth century.

Cardinal Jacques de Vitri, who lived about the year 1200, speaks of the magnetic needle, in his History of Jerusalem, as indispensable to those who make sea voyages. It has also been said that it was first brought to Europe, from the East, by Marco Polo. It is, however, certain that Vasco de Gama, the Portuguese navigator, used the compass in his voyage to India in 1497.

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* See Kircher, *De Magnete.*

(193.) Before it became the subject of accurate investigation, it was supposed that the direction of the compass was identical with that of the terrestrial meridian, and that it pointed due north and south. The discovery of its *variation*, and that the amount and direction of the variation are different in different places, is generally ascribed to Columbus in 1492. There appears, however, in a volume of MS. tracts in the University of Leyden, a letter dated 1269, by Peter Alsiger, in which the principal properties of the magnet are mentioned; and, among others, the *variation*. The honour of this discovery has also been ascribed to Grignon, a pilot of Dieppe, Sebastian Cabot, Gonzales, and others.

Accurate observations of the variation of the needle began to be made at Paris about the year 1550. At this time the variation was towards the east. It diminished in quantity, and became nothing in 1663; after which it passed to the west, increasing gradually till it attained a certain limit, after which it diminished.

(194.) The Dutch navigators, in 1599, also constructed accurate tables of variation.

(195.) In the year 1576, Robert Norman, a mathematical instrument maker in London, discovered the DIP. He found that the card of the compass near the north point was always depressed or inclined downwards, so that he was obliged to put a counterpoise on the southern pole of the needle, to keep it level.

(196.) Mentioning this circumstance to some scientific friends, he was advised to construct a needle on a horizontal axis, and to observe the position to which this downward inclination would bring the northern pole. He accordingly constructed the first DIPPING NEEDLE, and found the DIP to be about 71½°.

(197.) The variation of the needle was accurately observed at London by Burrough, the friend of Norman, who found that in the year 1581 it was 11° 15′ east. In the treatises extant by Norman and Burrough, no reference is made to any change, periodical or otherwise, either in the variation or the dip.

In the following century, the change to which the variation is subject was observed by Mair, Gunter, Gellibrand, and Bond. In the year 1599, Edward Wright wrote a work on the compass, which was published by Prince Maurice, lord high admiral of the United Provinces, in which the advantage of keeping registers of the variations observed on all voyages is urged. Thus the variation of the variation, not only as to time, but as to place, had at this period begun to receive the attention of those engaged in navigation.

(198.) When the influence of magnets on ferruginous matter came to be examined, it was soon apparent that they not only enjoyed the property of attraction, but that soft iron, so long as it remained within the sphere of their influence, actually acquired their own nature, and became magnetic also. When withdrawn from the influence of the magnet, the iron was found to return to its natural state. If, however, the iron, while influenced by the magnet, were twisted, filed, hammered, or submitted to other violence affecting its structure, it was then found to preserve the magnetism it had acquired, even when withdrawn from the magnet.

(199.) When iron filings were scattered over a sheet of paper under which a magnetic bar was placed, it was found that the metallic powder arranged itself in a particular manner, indicating different intensities of attraction in different parts of the bar. At a point near the centre the attraction seemed to cease, and to be augmented in each direction towards the extremities. The POLARITY of the magnet was consequently apparent. The points where the attraction seemed to be most intense were called the POLES.

When a magnetic bar was broken in the middle, or at the neutral point, each part was found to acquire separate polarity, and, like the original magnet, to have two poles with neutral points intermediate. When magnetism was imparted by a magnet to a bar of iron, the former lost none of its own magnetic force. Hence it was inferred that, in giving magnetism, the magnet lost none of the magnetic fluid.

(200.) When a magnet was brought in contact with a piece of steel, the effect was first discovered to be feebly but gradually increased, until the steel itself became a permanent magnet, but that this might be effected suddenly by friction. Bars of steel, thus magnetized, were called *artificial magnets*.

(201.) Gilbert, in his work already referred to published in the sixteenth century, mentions that the fact of magnetism being imparted to a bar of iron by the earth itself, was first discovered by examining the rod of the weathercock of the church of the Augustines at Mantua.

The possibility of conferring magnetism on substances which are not ferruginous was shown in 1733 by Brandt, who imparted magnetism to the metal cobalt. Croustedt, in 1750, showed that nickel is also susceptible of this property.

(202.) After philosophers had become familiar with the attractions and repulsions, the polarity and directive power of magnets, their attention was directed to the establishment of a numerical measure of the actual amount of attractive or repulsive force which they exerted under given circumstances. For a long period, no estimate of this was formed more accurate than the weight which, by attraction, the magnet was capable of supporting attached to a piece of soft iron adhering to it. In 1789, COULOMB applied to magnetism those beautiful and accurate instruments of investigation which were so successfully employed in electricity and other departments of experimental physics, and determined by their means the intensities and laws of magnetic forces. Two methods of measuring the force exerted were practised by him, similar to those by which electric attractions and repulsions had been measured. These were, the balance of torsion, by which the amount of the force was estimated by the action of a twisted wire or fibre of silk; and the observation of the number of oscillations which the attracted or repelled body made in a given time, on each side of the line of attraction or repulsion. By these means it was demonstrated that the force of a magnet was, *cæteris paribus*, in the direct ratio of the absolute intensity of the magnetism, and inversely as the square of the distance of the attracted or repelled body from it; a law identical in all respects with that by which electrical attractions and repulsions are governed. He also estimated, as he had done with electrified conductors, the distribution of magnetism on the surface of magnetized bars; and found that in bars of equal transverse section, of which the length was considerable compared with the magnitude of the section, the poles or points of maximum intensity were always at a distance of about an inch and a half from the extremities; and that, in very short bars, the poles are at one third of their length from the extremities, and that this latter position is the limit to which the poles approach as the bars are diminished in length.

(203.) In making artificial magnets, either by means of natural magnets or by other artificial magnets already made, the process first adopted was to rub the bar to be magnetized, from end to end, with one of the poles of the magnet by which it was to be magnetized. This method succeeded sufficiently well in magnetizing short needles; but, when applied to bars of any considerable length, it was attended with the liability of producing *consequent points*, that is, in fact, making the bar into a succession of magnets instead of a single magnet. Thus, a certain portion of the entire length, measured from the extremity, would possess two poles and an intermediate neutral point; then another succeeding portion of the length would possess other two poles with another intermediate neutral point, and so on.

(204.) In 1745, Dr. Gowan Knight of London practised an improved method. He placed two strong bar magnets end to end in the same line, the north pole of the one being in contact with the south pole of the other. Over them he laid the bar to be magnetized, its centre coinciding with the united ends of the two magnets, and its length laid along them. In this position the two magnets were drawn asunder lengthwise, their poles passing under each half of the length of the bar to be magnetized. By this method the bar acquired much stronger magnetism than by that which had previously been practised.

(205.) DU HAMEL further improved this process. The bar to be magnetized being placed between the pieces of soft iron, he took two bar magnets, and placing the north end of one and the south end of the other upon the centre of the bar, and inclining them at an angle of about 30° to it, he drew them upon it from the centre to the extremities, and repeated this process until the bar was strongly magnetized. This method was modified by MITCHELL, who placed a series of bars to be magnetized in the same straight line, with their extremities successively in contact. He then placed two bundles of strong magnets perpendicular to them, with their ends resting upon them, the northern end of one bundle and the southern end of the other being downwards. These two bundles of magnets, being attached to each other, were moved over the series of bars to be magnetized.

(206.) In 1789, COULOMB directed his investigations to the processes of producing artificial magnets. He showed that the susceptibility of bars of steel for magnetism depended conjointly on the temper of the steel and the force of the magnets, and that there was a certain limit to the magnetic force which a bar could receive. When a bar attained this limit, it was said to be magnetized to *saturation.*

(207.) The magnetic needles of ships' compasses being liable to great vicissitudes of temperature, it was a question of considerable importance to navigation whether heat affected the magnetic virtue. Gilbert was the first who observed that a magnet lost all its power when raised to a white heat, and on being cooled did not recover its magnetism. It was not, however, till a much later period, that the influence of heat on magnetism was submitted to accurate inquiry.

(208.) It was natural that the directive power of the magnet, and its application to navigation, should engross a large share of attention; and that the governments of maritime countries, more especially, should cause to be carefully and accurately observed all those phenomena by which that property was affected. The variation of the needle, and the changes periodical and local to which it is subject, were questions of the highest importance to national and commercial interests in every part of the world. So early as 1722, Graham had observed that in a given place the needle was subject to a *diurnal variation,* which was afterwards ascertained with great precision in different parts of Europe. It was observed by WARGENTIN, secretary to the Swedish Academy in 1750, and by CANTON in London in 1756, and subsequently by VAN SWIETEN, with nearly the same results. From all these observations it appeared that the north pole of the needle begins to turn westward at seven or eight o'clock in the morning, and continues to deviate in that direction till about two o'clock, when it becomes stationary, and soon begins to return eastward, arriving at the position it had in the morning at the same hour in the evening. Canton's observations showed that the amount of this deviation varied from seven to thirteen or fourteen minutes, being greatest at midsummer and least at midwinter, and increasing and decreasing gradually between these seasons.

More recently the same phenomenon has been observed by Colonel Beaufoy, Professor Hansteen, and others.

(209.) Cassini, who observed the diurnal variation of the needle at Paris, found that neither the solar heat nor light influenced it; for it was the same in the deep caves constructed under the Observatory in Paris, where a sensibly constant temperature is preserved, and from which light is excluded, as at the surface. In northern regions these diurnal changes are greater and more irregular; while, towards the line, their amplitudes are gradually diminished until at length they disappear.

(210.) The investigation of the changes produced in the direction of the needle, and in the intensity of the earth's attraction upon it, by change of place upon the surface, being a matter vitally important to commerce and navigation, has engaged the attention of all maritime and commercial countries, from an early period in the history of the mariner's compass. In fact, what may be not improperly called *magnetic geography* has been, and still is, a subject of profound interest, as well to the merchant as to the philosopher.

It has been already stated that the discoverer of the DIP found that at London a magnetic needle, free to move on an axis perpendicular to the magnetic meridian, presented its north pole downwards forming an angle of above 71°. If the instrument be carried northward, it is found that the dip gradually increases; and, on reaching a certain region near the pole, the needle would become vertical, the dip being then 90°, and its north pole pointing downwards. At such a place, the common compass needle, moving on a vertical support, would lose its directive power, and rest indifferently in any position. A place where these effects would be produced is called a NORTHERN MAGNETIC POLE.

(211.) If, on the other hand, the dipping needle were carried towards the equator, the magnitude of the DIP would be gradually diminished, until, on arriving at a certain region near the equator, the needle would become horizontal, and the dip would become nothing; and if the dipping needle could be carried round the globe, always following such a course as would allow it to retain its horizontal position, its course traced on the globe would be the MAGNETIC EQUATOR.

The magnetic equator does not coincide with the equator of the globe, nor is it a great circle of the earth. It never departs from the equator, however, more than twelve or thirteen degrees.

(212.) If, after passing the magnetic equator, the dipping needle be carried southwards, its south pole will dip or be directed downwards; and this dip will increase in magnitude as the needle approaches the south pole. A place near that pole, where the needle becomes vertical, is a SOUTHERN MAGNETIC POLE.

The first national project to determine the elements of magnetic geography was undertaken by the British government about the year 1700, when the celebrated Halley was commissioned to make a voyage with the view to collect the necessary observations. The results obtained by him were, however, deprived of the chief part of the advantages which ought to have attended them, because of the absence of uniformity in his instruments, and the neglect of making proper comparisons of them with others.

Since that period, observations have been made and recorded in all extensive voyages, and the data for the determination of the elements of this part of physical geography have been greatly augmented. The question being still, however, under investigation, the statement of the circumstances attending it will find a more proper place in the following treatise, than in the present historical summary.

IV. ELECTRO-MAGNETISM.

(213.) Those capital experiments by which the science of magnetism has been reduced to the rank of a branch of electricity, by showing that all magnetical phenomena are merely effects of electrical currents modified by physical influences peculiar to certain substances, are of so very recent a date that they can scarcely be considered as yet falling within the scope of Scientific History. Nevertheless, the important relations they bear to other parts of physics, the high generality of the phenomena themselves, and especially their susceptibility of being reduced to mathematical analysis, require that they should not be passed without some notice, even in a sketch so brief and rapid as the present. Since, however, it is proposed in these volumes to enter very fully into the details of the chief experiments which form the foundation of this part of electrical science, it will be sufficient here to notice concisely the chief results, in the order of their discovery, of those experimental investigations which may be regarded as forming the basis of the division of the science now denominated ELECTRO-MAGNETISM.

At a very early period in the progress of electrical inquiries, indications were observed of a relation existing between electricity and magnetism. Ships' compasses had their directive powers impaired by lightning, and sewing needles were rendered magnetic by electric discharges passed through them. The influence of electricity over the magnetic properties of iron had been sufficiently noticed to suggest to the clear and far-sighted mind of Beccaria a notion, which can scarcely be called a vague one, of that theory of terrestrial magnetism which may now be regarded as established on the basis of electro-magnetical phenomena.

No facts sufficiently clear and decisive to afford general conclusions were produced until the year 1280, which was signalised by the greatest discovery in physical science since the memorable invention of the pile.

(214.) Professor OERSTED, of Copenhagen, had promulgated certain theoretical views on the subject of the relations of electricity and magnetism in the year 1807, which obtained little attention, being unaccompanied by any new facts, and the community of science being then engrossed by the various and interesting experimental applications of the pile, and the magnificent series of discoveries which Davy was beginning to unfold. In 1820, however, Oersted supplied all that was wanting in 1807 to fix the attention of scientific inquirers — a capital experiment. In that year he announced the fact, that a magnetized needle placed near a metallic wire connecting the poles of a pile was compelled to change its direction; that the new direction which it assumed was determined by its position in relation to the wire, and to the direction of the current transmitted along the wire; that when the current was sufficiently strong, and the needle sufficiently sensitive, the latter always assumed a position at right angles to the wire; and that, whenever the direction of the current along the wire is reversed, the needle, making half a revolution, reverses the direction of its poles, keeping still perpendicular to the wire. This discovery being made known caused unqualified astonishment throughout Europe; the more especially, as all the attempts made before to trace the relation between the electric current and the magnet had been unavailing. The enthusiasm which had been lighted up by the great discovery of Volta twenty years before, and which time had moderated, was relumined, and the experimental resources of every cabinet and laboratory were brought to bear on the pursuit of the consequences of this new relation between sciences so long suspected of closer ties. The inquiry was taken up by AMPÈRE, ARAGO, BIOT, SAVART, and SAVARY, in France; by DAVY, CUMMING, and FARADAY, in England; and by DE LA RIVE, BERZELIUS, SEEBECK, SCHWEIGER, NOBILI, and others, in various parts of Europe.

(215.) Among these, in the inquiry now before us, AMPÈRE has assumed the first and highest place. No sooner was the fact discovered by OERSTED made known, than that philosopher commenced the beautiful series of researches which has since surrounded his name with so much lustre, and brought electro-dynamics within the pale of mathematical physics. On the 18th of September, 1820, within less than three months of the publication of Oersted's experiments in France, Ampère communicated his first memoir on electro-magnetism to the Academy of Sciences.

(216.) In this paper was explained the law which determined the position of the magnetic needle in relation to the electric current. In order to illustrate this, he proposes that a man should imagine the current to be transmitted through his body, the positive wire being applied to his feet and the negative wire to his head, so that the current of positive fluid shall pass upwards from the feet to the head, and that of the negative fluid downwards from the head to the feet. This being premised, a magnetic needle freely supported on its centre of gravity, so as to be capable of assuming any direction, and placed before him, will throw itself at right angles to him; the north pole of the needle pointing towards his left, and the south pole towards his right.

If the person through whose body the current thus passes turn round, so as to present his face in different directions, a magnetic needle, still placed before him, will have its direction determined by the same condition; the north pole pointing always to the left, and the south to the right.

In the same memoir were described several instruments intended to be constructed; especially spiral, or helical wires, through which it was proposed to transmit the electric currents, and which, it was expected, would thereby acquire the properties of magnets, and retain these properties so long as the current might be transmitted through them. The author also explained his theory of magnets, ascribing their attractive and directive powers to currents of electricity circulating constantly round their molecules, in planes at right angles to the line joining their poles; the position of the poles, on the one side or the other of these planes of revolution, depending on the direction of the revolving current.

(217.) On the 25th of the same month, Ampère communicated to the Academy another paper.* In this he delivered the results of his experiments on the reciprocal attractions and repulsions of electric currents acting on each other. He showed that two straight wires along which currents are transmitted will attract or repel each other, according to the direction of the currents. Let a line be imagined intersecting both wires at right angles. If both currents move towards this perpendicular or both from it, the wires will attract each other; but, if while one of the currents moves towards this perpendicular the other moves from it, then they will repel each other. If the wires be parallel to each other, they will attract or repel each other, according as the currents move in the same or opposite directions. If the wires be in the same plane, but not parallel, their directions will meet if produced: in this case they will attract each other, if the currents be both directed *towards*, or *from*, the point where their directions meet; and they will repel each other, if one current be directed towards, and the other from, that point.

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* Annales de Chimie et Physique, tom. xv. 59—170.

(218.) In the same paper he proposes the hypothesis of currents of electricity circulating round the terrestrial globe, from east to west, in planes at right angles to the direction of the dipping needle, to account for the phenomena of terrestrial magnetism.

These researches proceeded with unusual celerity. On the 9th of the following month (October), three weeks after the reading of the last-mentioned paper, he presented another memoir to the Academy, in which he investigated the properties of currents transmitted through wires forming closed curves (courbes fermées), or complete geometrical figures.

(219.) While Ampère was proceeding with these researches, Arago directed his inquiries to the state of the wire through which the current was transmitted, more especially with a view to determine whether every part of its surface was endowed with the same magnetic properties. With this view he placed iron filings within the sphere of attraction of the wire, and found that they adhered to it, so as to form concentric rings upon it. The moment the connexion of the wire with the pile was broken, and the current was no longer transmitted along it, the filings fell off and all attraction disappeared.

(220.) By a process inferred from the theory of Ampère, M. Arago succeeded in imparting permanent magnetism to needles and bars of steel by means of the electric current. This was accomplished by making a spiral of wire, through which the current was transmitted, while the needle or bar to be magnetized was placed within its coils. The position of the poles of the magnets thus made depended on the direction of the screw, or helix, formed by the conducting wire. If the wire formed a right-handed screw, the poles were placed in one direction; and if it made a left-handed screw, they were reversed. When the wire was made to form a succession of screws alternately right-handed and left-handed, the bar was magnetized with a corresponding series of *consequent points*. The same results were obtained whether the electricity transmitted through the wire proceeded from a Voltaic apparatus or from the common electrical machine.*

(221.) At the same time, or very little later, and before the information of Arago's experiments reached England, Davy succeeded also in imparting magnetism to needles by the Voltaic current, and by common electricity; and also showed the effect of the conducting wire on iron filings.†

M. Ampère, with the view of more completely developing the action of electric currents and magnets separately and on each other, contrived various methods by which wires, formed into parallelograms, circles, and other geometrical figures, could have a current transmitted round them, and be at the same time so supported or suspended as to be capable of assuming any position or direction to which their mutual attraction, or the attraction between them and magnets placed near them, or the influence of the magnetism of the earth upon them, might dispose them. These contrivances afterwards became instruments by which many important experiments were made; the first of which was communicated to the Academy on the 30th of October, 1820. This was the fact, that a wire forming a plane geometrical figure through which the electric current is transmitted will, if free to move, dispose itself so that its plane shall be at right angles to the dipping needle.

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* Annales de Chimie et Physique, tom. xv. p. 93.

† Letter to Wollaston, 12th Nov. 1820, Phil. Trans. 1821.

(222.) On the same day, MM. BIOT and SAVART communicated to the Academy the results of experiments made with the view to determine the law of the mutual attraction and repulsion of electric currents. The results of these experiments were reduced to analytical investigation by LA PLACE, who showed that the law resulting from them was, that the attraction or repulsion of each elementary part of the current diminishes in the same ratio as the square of the distance of the object on which it acts increases; a law identical with that of all other modes of electrical attraction and repulsion. The effect of the obliquity of the current to the direction in which the force acted was also determined.

(223.) On the 4th of December following, M. AM-

PÈRE read to the Academy the memoir which contains the reduction of the phenomena of electro-magnetism to mathematical analysis. He showed that all the various phenomena attending the action of magnets on each other, of electric currents on magnets, and of magnets on electric currents, and, in fine, of electric currents on each other, could be derived, by mathematical calculation, from formulæ expressing the action of two infinitely small elements of electric currents, acting on each other in the direction of the line joining their middle points. The discussion of this subject was concluded in another memoir, read to the Academy on the 8th and 15th of January, 1821.

(224.) This year, 1821, was signalized by the commencement of the labours of FARADAY in electro-magnetism. This philosopher, who has since attained such well-merited celebrity, realized a suggestion which originated with Dr. Wollaston. A magnet being placed in a vertical position, a wire was so suspended that, while the electric current was passing through it, it was capable of moving round the axis of the magnet so as to describe a conical or cylindrical surface. While the current was maintained, the wire took spontaneously this motion; and when the direction of the current along it was reversed, it reversed its motion, and turned round the magnet the contrary way. Reversing these conditions, and instead of fixing the magnet and leaving the wire free, he fixed the wire, and so adjusted the magnet that it was at liberty to revolve round the wire as an axis. When the current was transmitted through the wire, the magnet spontaneously revolved round it; and when the direction of the current through the wire was changed, the motion of the magnet was reversed.

FARADAY attempted, without success, to cause a magnet to revolve on its own axis; but, the memoir containing the account of his experiments being published in France, AMPÈRE succeeded in producing rapid rotatory motion of magnets on their own axes, and showed that this and the two former results of Faraday's experiments followed as necessary consequences of his own mathematical principles. He also showed that the same effects could be produced with helical currents, thus affording a further corroboration of his theory of magnetic action.

(225.) Immediately after the publication of these experiments of Faraday, DAVY thought that the effect of the magnet on the current might be obtained in a more simple state by transmitting the current through a fluid conductor, and exposing the conductor to the action of a strong magnet. With this view, two copper wires, about a sixth of an inch in diameter, coated with sealing-wax, and flattened and polished at the ends, were cemented into two holes three inches apart in the bottom of a glass dish, so that the direction of the wires was perpendicular to the dish. The coating of sealing-wax rendered the wires non-conductors, except at their flattened and polished ends, which were not coated. Mercury was poured into the dish so as to cover the ends of the wires to the depth of the tenth or twelfth of an inch. The parts of the wires proceeding from the bottom of the dish were now put in connexion with a powerful Voltaic battery, the positive current flowing into the mercury at one wire, and passing from it at the other. The moment the current commenced, the mercury over each wire was thrown into a state of violent agitation. Its surface was raised into the form of two small cones one over each wire; waves flowed off in all directions from these cones. On holding the pole of a powerful bar magnet some inches above one of the cones, its vertex was lowered; and according as the magnet descended towards the mercury the subsidence of the cone continued, and the propagation of waves around it ceased, until at length the surface of the mercury became perfectly level, and a slow revolving motion of the mercury round the pole of the magnet began to be manifested. As the magnet was brought still closer to the mercury this gyration of the fluid became more rapid, and the centre round which the gyration took place (which was directly over the end of the wire) became depressed. The rapidity of the rotation of the mercury, and the depression of the centre of the vortex, continued to increase as the magnet was brought nearer to the mercury, until no more mercury remained over the end of the wire than was barely sufficient to cover it. This rotation took place with either pole of the magnet, and over either wire, changing its direction when either the pole of the magnet or the direction of the current was changed. It is evident that these phenomena are in accordance with, and referable to, the same general law as those previously discovered by Faraday. The same effects were observed when fused tin was substituted for mercury, and when steel wires were used to conduct the current. The current was also conducted to the dish by tubes filled with mercury, with like results.*

(226.) In order to determine whether the matter forming the conductor along which the electric current passed had any influence on the electro-magnetic phenomena which at this time engaged the attention of philosophers, Davy placed two pieces of charcoal in connexion with the wires of a powerful Voltaic battery, and, by presenting their points towards each other, at a distance varying from one to four inches, according to the density of the air in which the experiment was made, he obtained a column of electric fluid formed by the current passing through the space between the charcoal points. This current was not transmitted, as usual, along any conductor, but merely passed through the air between the points; and its presence was rendered manifest by the light evolved. When a powerful magnet was presented to this column, with its pole at a very acute angle to it, the column was attracted or repelled with a rotatory motion, or made to revolve by placing the poles in different positions, in the same manner as metallic wire conducting the current would have been. The electric column was more easily affected by the magnet, and its motion was more rapid, when it passed through dense than through rarefied air; and, in this case, the conducting medium, or chain of aeriform particles, was much shorter.†

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* Phil. Trans. 1823; also Davy's Works, vol. vi. p. 258.

† Phil. Trans. 1821; Davy's Works. vol. vi. p. 232.

While these investigations were proceeding in France and England, the discoveries to which they led conducted a German philosopher to the invention of an instrument of physical inquiry of surpassing beauty and utility, and equalled in importance by none which had appeared since the balance of torsion.

(227.) The *multiplier*, or, as it has been called in England, the *galvanometer*, invented by SCHWEIGER, is an instrument by which the presence of an electric current is detected, and its intensity measured. It is based upon the fact, that a wire through which a current passes will have a tendency to turn a magnetic needle at right angles to it. By this beautiful instrument the most feeble currents may be made manifest, and their intensities compared. It is various in its construction, according to the nature and power of the electric currents intended to be observed, but generally consists of a rectangular frame of wood, round two parallel sides of which a copper wire, lapped with silk, is rolled, so that the coils of wire shall be close beside each other, and parallel in their general direction to the other two sides of the frame. Within the frame, and between the two surfaces formed by the coils of wire, is suspended a magnetic needle. If the frame be so placed that the needle, when at rest, shall be parallel to the coils of wire, these coils will be parallel to the magnetic meridian. Matters being thus disposed, let the extremities of the wire be put in connexion with the poles of a Voltaic pile. The current passing through the wire will act upon the needle, and each coil of the wire will affect it as a separate current, so that the total effect will be in proportion to the number of coils. If the current in the lower coils moved in the same direction as the upper, it would have a contrary effect on the needle; but, by the manner in which the wire is carried round the frame, the systems of inferior currents are contrary in their direction to the superior currents, and they have, consequently, the same effect on the needle. If the effect of the current thus multiplied be sufficient, the effect of the earth's magnetism will be overcome, and the needle will be turned at right angles to the wires, and, consequently, will take the direction of magnetic east and west; but if the force of the current be insufficient for this, the needle will be deflected at some definite angle with the magnetic meridian, the magnitude of which angle will supply the means of estimating the force of the current.

It is evident that the sensibility of this instrument will be augmented in proportion as the magnetism of the needle is enfeebled, and the number of coils of wire augmented.

The direction of the current is indicated by the direction in which the deflection of the needle takes place. If the north pole of the needle be deflected towards the east when the current passes in one direction through the wire of the multiplier, it will be equally deflected towards the west when the same current is reversed.

(228.) When Ampère had demonstrated the reciprocal action of electric currents on each other and on magnets, he showed that the terrestrial globe exerted an influence on magnets freely suspended, and on electric currents transmitted through wires so supported as to be capable of obeying any forces exerted upon them, identical in all respects with the influence which a sphere would exert round which a wire coiled so that its coils shall nearly coincide with the parallels of latitude, through which wire an electric current is transmitted, running continually from east to west, or contrary to the diurnal motion of the earth; or, since the wire in such case is merely necessary to conduct the electricity, the phenomena of terrestrial magnetism only require the admission that a series of electric currents continually circulate round the globe, according to lines which intersect the magnetic meridians perpendicularly.

(229.) To present an experimental verification of this theory, M. Ampère constructed a plane geometrical figure, a circle, for example, of wire, and suspended it in such a manner that, while the current circulated upon it, the figure was capable of moving on a vertical axis through its centre of gravity. It was observed to throw its plane into a position at right angles to the magnetic meridian. When the current was reversed, it turned round through 180°, and reversed its plane. When a helix was suspended on its centre of gravity, and a current was transmitted through the wire, it exhibited all the properties of a magnet; when suspended on a vertical axis, it assumed the direction of the magnetic meridian; and when suspended on a horizontal axis at right angles to the magnetic meridian, it threw itself parallel to the dipping needle.

The hypothesis of Davy, that the nucleus of the globe consisted of the metallic bases of the alkalies and earths, and that its surface was oxydated, supplied Ampère with strong grounds of probability in support of these theoretical ideas of terrestrial magnetism. It was easy to imagine that, at the surface of contact of the metallic nucleus and the surrounding shell of oxydated matter, there were constant chemical actions in progress, which might produce a series of electric currents at some distance below the surface of the earth, and that these currents, acting through the shell of oxides, would produce the phenomena of terrestrial magnetism.

(230.) In the same year, M. de la Rive, of Geneva, published a memoir, in which he showed that when a current is transmitted through a closed circuit of a rectangular form, for example, it affected only the sides which have a vertical position. He established, as a general law, that a vertical current, capable of revolving round a fixed vertical line as an axis, will place itself so that the plane passing through its own direction, and the axis round which it revolves, shall be at right angles to the magnetic meridian, the side on which the current descends being on the east of the axis, and the side on which it ascends being on the west.

He also showed that a horizontal current, though not susceptible of being influenced by the magnetism of the earth, is not therefore free from all action; on the contrary, he proved that when it is free to move parallel to itself, it will move in this manner in the one direction or the other, according to its own direction; and that this motion will equally ensue in all positions in which it may be placed, whether it be directed north and south, east and west, or in any intermediate azimuth.

These laws, proved experimentally by M. de la Rive, were immediately shown by M. Ampère to be direct consequences of his theoretical principles.

(231.) In the year 1827, M. SAVARY directed his labours to follow out the researches on the power of the Voltaic current to impart magnetism to iron, which had been demonstrated by the experiments of Davy and Arago. M. Savary discharged a Leyden jar through a metallic wire, needles placed near which were found to be magnetized, and the strength of the magnetism imparted to them was observed to vary with their distance from the wire. Being placed at various distances from it, the magnetizing power of the current was not found either continually augmented, or continually decreased; but, as the needle receded, it first increased and then diminished, attaining a maximum at a certain position. He also showed that as the distance varied, not only the intensity of the magnetic force passed thus successively through maxima and minima, but the polarity was reversed, taking alternately one direction or the other. These alternations of intensity and polarity appeared to be determined in a great measure by the weight, diameter, and conducting power of the wire, and the strength of the electric discharge.

(232.) One of the most novel and unexpected circumstances attending the experiments of M. Savary, was the manner in which he showed that the magnetizing influence of the current was modified by transmitting it through other metals. When the needle to be magnetized was enveloped in metallic leaf, the magnetism it received was augmented. By gradually increasing the thickness of its metallic coating, the force of the magnetism it received increased by degrees till it attained a maximum, after which it diminished; and, by further augmenting the thickness of its coating, it was diminished so as to be equal to the magnetism it would receive without any coating. Copper, tin, gold, silver, and mercury, used as coating, were found to possess this property in different degrees. The force of the electric charge transmitted through the wire was found to have a singular influence on the phenomenon; for, according as this force was increased or diminished, different thicknesses of the same coating were necessary to produce equal effects. These considerations also affected the direction of the polarity.

(233.) These facts appeared to M. Savary to be scarcely compatible with any hypothesis which requires the admission or the translation of electric matter by the current; and he considered that they indicated rather that the current proceeds from a system of undulations propagated along the wire, and transmitted by it laterally to adjacent media.

V. THERMO-ELECTRICITY.

(234.) The fact that a derangement of the equilibrium of temperature was attended with the evolution of electric effects was observed by Volta, and subsequently by Dessaignes. Volta found that a plate of silver, one end of which was more heated than the other, produced Galvanic effects; and Dessaignes observed that convulsions were produced in the frog, when the muscles and nerves were connected by a silver spoon in which lighted charcoal was placed. These isolated observations, however, led to no conclusions affecting the progress of discovery.

Immediately after the discovery of OERSTED became known throughout Europe, Professor SEEBECK, of Berlin, engaged in a series of researches on the Voltaic effects produced by derangement of temperature; and communicated to the Academy of Sciences of Berlin, during the years 1821 and 1822, the results of his experiments, which were published in the Transactions of that body, and form the basis of whatever has since been collected under the title of THERMO-ELECTRICITY.

(235.) A rod of copper being bent into a semicircle, a bar of antimony was soldered to it, so that the two metals had the form of a stirrup. The temperature of one of the points of junction of the metals was raised, while that of the other was unchanged. An electric current was immediately excited, passing from the copper at the heated point through the antimony. The intensity of the current was augmented by augmenting the difference of temperature of the two points of connexion of the metals, and the direction of the current was reversed when the source of heat was removed from one point of junction to the other. The current was rendered manifest by its power to deflect a magnetic needle.

Seebeck observed similar effects by combining various other metals in pairs; and found that the relative electric state of the metals did not correspond with that assigned to them in Volta's theory of contact. He also observed that currents were produced by inequality of temperature in bars of a single metal, when they have a crystalline structure; and suggested that the changes of temperature of the metallic nucleus supposed by Davy to be within the external crust of the earth, might produce those currents circulating round the globe to the influence of which Ampère ascribed the magnetism of the globe.

(236.) In the year 1823, these inquiries were prosecuted by the Chevalier YELIN, and MM. MARSH and CUMMING.* The first investigated the influence of the nature and form of homogeneous metals on the direction and intensity of the electric current. The two latter philosophers produced the revolution of thermo-electric currents round magnets. Soon afterwards MM. OERSTED and FOURIER communicated to the Academy of Sciences a series of experiments on currents obtained by thermo-electric piles, made by combining bars of antimony and bismuth in a series. The alternate points of junction were heated, and the current was manifested by the deflection of a magnetic needle. This deflection, though considerable, was not observed to increase in proportion to the number of thermo-electric elements constituting the pile. They attempted, without success, to effect chemical decompositions by the current thus obtained. This has, however, been since effected by Becquerel, by exposing to the action of the thermo-electric current solutions easily decomposable. M. Bottot, of Turin, has also succeeded in decomposing water, and various solutions, by the thermo-electric current obtained from a pile formed of a series of wires of platinum and iron.

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* Bibl. Univ. tom. xxiv. xxv. xxvii. and xxix.

(237.) The result of these and subsequent investigations of Seebeck, Becquerel, and others, has led to the establishment of the following series of metals possessing thermo-electric excitability, in the order in which they stand.

1. Bismuth.
2. Platinum.
3. Mercury.
4. Lead.
5. Tin.
6. Gold.
7. Silver.
8. Copper.
9. Zinc.
10. Iron.
11. Antimony.

If a thermo-electric couple be formed by any two metals in this series, the positive electricity at the heated point will pass from that metal which holds the higher to that which holds the lower place in the series; consequently, each of the metals in the series is thermo-electrically positive to all above it, and negative to all below it.

Becquerel showed that when one end of a homogeneous metallic wire was heated, and brought into contact with the other end, an electric current was formed, passing from the heated to the cold part of the wire across the point of contact. These inquiries were attended with several curious and important results, when the temperatures were carried to extreme points in the case of certain metals; but as they will necessarily form a part of the subject matter of these volumes, it is needless to enter here into any details respecting them.

(238.) In concluding this brief outline of the history of the progress of electrical science, it may be proper to remind the reader, that the necessary limits of such a compendium as the present have precluded many details which would be regarded with interest by those who prosecute scientific inquiries. The chief discoveries only, including those which have had most influence in establishing general theories, were entitled to any detailed notice; and the labours of contemporary philosophers have been for the most part excluded, as they will find a more suitable place in the manual which we now offer to the public.

BOOK THE FIRST.

ELECTRO-STATICS.

CHAPTER I.

DEFINITIONS AND PRIMARY FACTS.

(1.) As the observation of the phenomena of nature progressively unfolded those general laws which constitute the body of physical science in its present advanced state, effects which were tangible, and admitted of direct numerical estimation by weight and measure, first pressed themselves on the attention of philosophers. Weight, extension, magnitude, and form, are properties inseparable from matter, in whatever state it may be, and divested of which, indeed, it is impossible to imagine its existence. Such qualities, and their consequences, were therefore early subjects of investigation. Some of them are not only inseparable from the matter to which they appertain, but are unchangeable in quantity or degree so long as the identity of that matter continues. The weight, or inertia, of a body must be the same so long as no particle is added to it or subtracted from it; and although the effects of the mutual attraction of its constituent molecules, which determine its hardness, brittleness, ductility, and elasticity, may be modified by the action of other antagonist forces depending on the agency of heat and the play of the chemical affinities, yet these molecules can by no means be deprived of any portion of that reciprocally attractive force. It is otherwise with the class of physical agents called the *imponderables* one of the most remarkable of which is about to engage our attention. Material substances are composed of particles or atoms, maintained in their position with a greater or less degree of mutual proximity by the operation of forces, the sphere of whose action is extremely minute. But these constituent particles, though in close juxtaposition, are not in absolute contact: on the contrary, it is demonstrable that they are separated by interstitial spaces, which, though small in magnitude compared with the total dimensions of the bodies they pervade, are great, — perhaps infinite, — compared with the dimensions of the molecules which they separate. Is evidence required of this proposition? Take the most solid and adamantine body, and accurately measure its volume. Let it then be exposed to cold, so as to reduce its temperature any required number of degrees. If its magnitude be now measured, it will be found to be less than before. But this diminution of volume has not arisen from any loss of ponderable matter, for the body before and after the change of temperature would be found to have the same weight. It has, therefore, contracted its dimensions by the nearer approach of its constituent particles to each other. Their mutual attraction has been rendered more energetic by the diminished force of that agent which keeps them separated; but had they been in actual contact before the change of temperature, they would have had no room to approach each other, and therefore no diminution of volume would have ensued. To this diminution of volume, of which the hardest and most solid bodies are susceptible, there is no known limit, save that which is imposed on the reduction of their temperature; and the spaces which separate their particles must, therefore, bear to the dimensions of the particles themselves a proportion indefinitely great.

These interstitial spaces or pores, though void of all ponderable matter, are nevertheless the region of physical agents of vast importance in the great economy of nature. The researches of modern philosophers respecting the phenomena of light and heat have rendered it probable, if not certain, that a subtle ethereal fluid, so attenuated as not to possess any discoverable weight, pervades the universe, and fills the pores of all material substances; and that the phenomena of light and heat are merely vibrations excited in this fluid by mechanical causes, and transmitted by its proper elasticity in the same manner as sound is excited in, and transmitted through, the air, or undulations produced and propagated on the surface of a liquid.

Admitting the existence of this imponderable ether pervading the dimensions of bodies, we are prepared for classes of phenomena which may have a dependence on the state of such a fluid, and which, though intimately connected with the bodies themselves, shall nevertheless have no discoverable relation to their mechanical properties. Such are the effects ascribed to the agency of *Electricity.* While the material elements of the body are neither augmented nor diminished in the smallest degree by the presence of the electrical influence, — while that agent neither gives to nor takes from the constituent molecules of the mass any tangible or ponderable principle, — it is nevertheless attended with the most tremendous mechanical effects. The lightning, which has neither momentum, weight, nor dimension, — which is an imponderable and impalpable essence, — nevertheless tears up and splits in pieces the largest trees of the forest, razes to the ground the most solid structures, and strikes with instant death the most powerful animals.

(2.) To explain the phenomena which first drew the attention of philosophers to the agency of electricity, and which still present the easiest means of rendering intelligible the first and most simple laws of electrical influence, let us suppose a rod or tube of glass, which has for any considerable time remained untouched by other bodies, to be presented to a feather suspended by a fine thread of silk: the tube may be made to approach and touch the feather, and may be withdrawn from it, but no other effect will ensue; the feather will maintain its position undisturbed. Let the tube, however, now be briskly rubbed with a dry woollen cloth, and then presented to the feather: when the side of the tube where it has been rubbed is brought near the feather, the latter will manifest a tendency to approach the tube; and when the distance is further diminished, the feather will suddenly fly to the tube, and adhere to it.

It is apparent, then, that friction with a woollen cloth has imparted to the glass a property which previously it did not possess, in virtue of which it exerts an attraction on the matter of the feather, and produces a distinct and measurable mechanical effect. The mechanical properties of the tube, and cloth with which it was rubbed, remain, however, unchanged, neither having gained or lost a single particle of ponderable matter.

This property is not peculiar to glass. If a stick of sealing-wax, or a piece of resin or amber, be rubbed in a similar manner, these substances will manifest the same attraction for the feather.

Neither is a feather the only substance which will be affected by this attraction. If bits of paper, straw, or other similar light substances, be suspended like the feather, they will be similarly attracted by the glass.

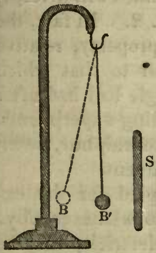
(3.) The physical agent, whatever be its nature, which is thus called into operation by the friction of the glass, wax, resin, or amber, and to which the attraction is due, is called *Electricity.*

The first substance which was known to be capable of acquiring this property was *amber,* in which it was observed by Thales, about six centuries before the birth of Christ. The name *electricity* has therefore been given to this part of physical science, from the Greek word ἤλεκτρον (electron), signifying *amber,* the first substance in which the property had been observed.

(4.) To examine all the circumstances attending the phenomena to which we have above referred, let us suppose that pieces of glass, sulphur, resin, and sealing-wax are provided, formed into cylinders of such a magnitude as to produce the desired phenomena with sufficient intensity. For this purpose, cylindrical pieces of these substances should be about an inch in diameter, and twelve or fourteen inches in length. Let a small ball, with a diameter of about the eighth of an inch, be turned from the pith of the elder tree; and let it be suspended from a hook by a fine silken thread, supported by a convenient stand, as represented in *fig.* 1. This ball will supply the place of the feather in the experiments already explained.

Let a glass rod, S (*fig.* 1.), be now briskly rubbed with a woollen cloth previously well dried, and let it be presented to the pith ball B. The ball will approach the glass, and adhere to it. If they be separated by drawing the glass away, and afterwards the glass be again presented to the pith ball as before, the ball, instead of being attracted, will recoil from it, taking the position B′, and will remain in that position so long as the glass is held near it; but when the glass is removed, the ball will again descend to its natural position of rest,—the silken string by which it is suspended recovering its vertical position.

Fig. 1.



If a stick of resin, sulphur, or sealing-wax be similarly rubbed, and presented to the pith ball, the same effect precisely will ensue.

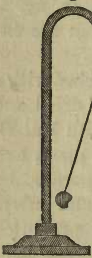
From these experiments the following consequences may be inferred: —

1st. By the friction of the dry woollen cloth, a quality is imparted to glass, sulphur, resin, or sealing-wax, in virtue of which the pith ball is attracted to it.

2d. After being brought in contact with the surface of the glass, sulphur, resin, or sealing-wax, and separated from it, the state of the ball is changed; and it acquires a property, relative to the glass, sulphur, resin, or wax, in virtue of which, instead of being attracted, it is repelled.

(5.) Let two pith balls be now suspended from the same hook by two separate silken threads of the same length, so that the balls shall rest in contact. Let the glass rod, after being rubbed as before, be presented to these balls. It will attract both of them, and they will adhere to it. Let the glass rod be then withdrawn from them. They will no longer fall into the vertical position, and rest in contact with each other, as they did before they were touched by the glass: on the contrary, they will repel each other, so that the threads by which they are suspended will diverge, as represented in *fig.* 2. In fact, the balls will acquire a property, relative to each other, similar to that which the glass and the single ball had after contact in the preceding experiments.

Fig. 2.



The same effects would ensue if the sulphur, resin, or sealing-wax were used in the experiment.

(6.) Whatever theory may be adopted for the explanation of electrical phenomena, or to whatever physical agency the immediate effects of electricity may be ascribed, it will be convenient to express the phenomena which are to be described, and whose laws are to be developed, by terms which must unavoidably have occasional reference to one or other of the various hypotheses which have been invented to connect together, systematize, and generalize the facts which form this branch of physical science. We shall thus frequently refer to electricity as a *fluid*. In so doing, however, we desire for the present to be understood as using the phrase *electric fluid*, and similar terms, merely to express ascertained and observed *facts*, without asssuming anything respecting the physical agent from which electrical phenomena proceed. Whatever the nature of electricity may be,— whether it be a fluid *sui generis* which pervades all bodies, and possesses distinct properties; or a property of the fluid or fluids from which the effects of heat, light, and other imponderable agents arise; or whether, finally, it be an affection of the constituent molecules of matter,—

the effects we shall have to explain being such as might and would belong to an elastic or self-expansive fluid, we shall apply that term to express the physical agent, whatever it may be, to which such effects belong; and this, and this only, is what we would be understood to convey whenever the phrase "electric fluid" is used.

(7.) The preceding experiments indicate the transmission of a physical influence from the glass to the pith balls, which influence the glass itself acquired by friction. The electric fluid, produced on the surface of the glass by friction, being self-expansive, and the surface of the pith balls being of a nature to allow an unobstructed passage to it, a portion of the fluid distributed upon the glass at the point of contact passes, by virtue of its expansive power, to the surface of the pith balls; and this fluid being self-repulsive, the pith ball, when covered with it, is repelled by the glass.

That the pith ball, after contact with the glass, possesses the property which by friction was imparted to the glass, may be proved by causing the ball to approach another ball in its natural state. The latter will then be attracted by the former in the same manner as it would be attracted by the glass; and, after contact, the two balls will repel each other in the same manner as that in which the glass repelled the pith ball after contact in the first experiments, and in the same manner as the two pith balls repelled each other after they had both touched the glass.

(8.) When glass, sulphur, resin, sealing-wax, or any other substance susceptible of like effects, is submitted to friction, so as to acquire the property here described, such surface is said to be *excited*; and when, by contact with it, a pith ball or any other body acquires a like property, that body is said to be *electrified*.

(9.) Besides the effects of attraction and repulsion here described, an electrified or excited body is attended with other effects, not less remarkable, which will be more fully developed as we proceed. If a glass tube, excited by friction, be brought near the surface of the skin, a sensation will be produced, when the distance is diminished to a certain limit, similar to that which is felt when we touch a cobweb. Also, if a strongly electrified or excited surface be brought nearly into contact with the knuckle, or with a small metallic ball, a little luminous spark, accompanied with a cracking noise, will be observed to pass between the electrified body and the knuckle or to the metallic ball. If the experiment be made in the dark, this spark will be more distinctly visible.

If any of the bodies above mentioned be excited by friction in the dark, a blueish light will be observed constantly to follow the motion of the cloth with which the friction is performed.

(10.) Besides the substances above mentioned, there are a vast number of others capable of evolving electricity by friction in the same manner. All vitreous and resinous bodies whatever produce like phenomena in different degrees. They are also obtained with stuffs of silk of every kind.

(11.) The metals form a class of bodies which at first appear incapable of producing these effects. If a tube or rod of metal be taken in one hand, and any stuff by which other substances are excited be briskly rubbed upon it with the other hand, none of the usual indications of electricity will follow. The metal will not attract light substances; it will have no effect upon the pith balls; no luminous appearance will follow the rubbing, nor will any effect be produced upon the organs by approaching or touching it. A more close and attentive examination will show, however, that this absence of electrical effects does not arise from the circumstance of the metal being incapable of evolving the electric fluid by friction, but that the proper effects of such an evolution of electricity are masked by others depending on a property of the metals in which vitreous and resinous substances do not participate. To make this apparent, let us suppose that, instead of holding the metallic tube in the hand, we attach to the end of it a glass handle, which enables us to hold it in a convenient manner for rubbing it, but at the same time without touching it. If we now rub it as before, taking care not to touch it except with the cloth with which it is rubbed, it will be found to acquire the same electrical properties as the glass, sulphur, and resinous substances acquired in the former experiments.

(12.) The possibility of exciting electricity on the surface of metals may also be shown in the following manner. Let a tube of metal be suspended by a silken cord, and let it be struck two or three times with the skin of a cat; it will be then found to be electrified, or excited, in the same manner as the glass or resin.

So long as the metal thus excited is kept suspended by silk, or supported by glass, the electrical state of its surface will continue; but if it be touched, even for an instant, by the hand, or by a rod of metal held in the hand, it will suddenly lose its electricity altogether.

There are a variety of other substances, besides silk and glass, by which metal may be suspended or supported so as to enable it to be excited by friction: if it be supported, for example, by any resinous substance, it will be equally capable of being excited.

(13.) These effects are easily explained. Metallic bodies are susceptible of excitement as easily as the vitreous or resinous bodies; but they likewise possess a property which the latter do not enjoy, in virtue of which the electric fluid moves freely upon them. In the experiment, therefore, in which a metallic rod held in one hand is rubbed by a woollen cloth held in the other, the electricity which is excited upon the rod of metal passes away through the hand to the body of the operator. That portion of the electricity which is nearest the hand first passes away, and the facility with which the electricity moves upon the surface of the metal causes the remaining portion of it immediately to follow. As fast, therefore, as the electric fluid is evolved by the friction upon the metal, it passes away to the hand and thence to the body of the operator, and no portion remains on the surface of the metal.

The case, however, is quite otherwise with a rod of glass similarly treated. Unlike metallic surfaces, the surface of glass does not give free motion to electricity. On the contrary, the electricity appears, as it were, to be so obstructed in its movement over a vitreous surface, that it may be accumulated in one part, while another part is altogether free from it. If, therefore, a rod of glass be held in one hand, while with the other it is excited by friction, that part of the rod which has been thus submitted to friction will be covered with electricity, whilst that part which is held by the hand will be free from it. The electricity which is accumulated on the part of the surface which has been rubbed, does not, as was the case with the metallic surface, pass over the surface to the hand and thence into the body of the operator, but remains on that part of the surface where it was excited. The glass, however, may be deprived of its electricity by the operator passing his hand in contact with that part of the surface which has been excited. All the electricity produced upon the glass will then pass into the body of the operator.

(14.) These and similar effects lead to the distribution of natural substances, in reference to their electrical properties, into two great classes;—those which, like the metals, allow the free motion of the electric fluid over their surfaces; and those which, like glass and resinous substances, do not allow its free motion. The first are called *conductors* of electricity, and the second *non-conductors*.

(15.) The impracticability of producing electrical effects by friction upon the metals and similar substances, when the experiment is conducted in the same manner as with glass or resin, for a long time led to the supposition that such substances were incapable of evolving electricity, and hence they were called *non-electrics* or *analectrics;* while, on the other hand, vitreous and resinous substances, and the like, were called *electrics*. When, however, it was discovered that the absence of the electrical effects on conducting bodies, when excited by friction or otherwise, was owing not to their inability to evolve electricity, but to the escape of this electricity as fast as it was evolved, these terms were abandoned as expressing properties and effects which have no actual existence; and the more appropriate terms *conductors* and *non-conductors* were retained.

(16.) When it is desired to preserve on a conducting body the electricity which has been imparted to it or excited upon it, it is usual either to suspend or support it by a non-conducting substance: such a substance, not giving free passage to the electricity, prevents its escape from the electrified body. An electrified body thus placed is said to be *insulated;* and non-conductors are accordingly called also *insulators.*

(17.) Atmospheric air must manifestly belong to the class of non-conducting bodies; for if it gave a free passage to electricity, the electrical effects excited on the surface of any body surrounded with it would quickly pass away, and no electrical phenomena of a permanent or durable nature could be produced, unless the bodies experimented on were removed from contact with the air. On the contrary, it is found that resin or glass, when submitted to friction, preserves its electrical properties for a considerable time, even though surrounded by atmospheric air.

(18.) In the experiments with the pith balls already explained, we have stated that the balls should be suspended by threads of silk. If, instead of silk threads, fine metallic wires had been used, the same effects would not have ensued. The balls could not then have been permanently electrified by contact with the excited tube, and consequently the effects of electricity upon them would not be manifested.

The cause of this admits of easy explanation. When the pith ball touches the glass, being itself a conductor of electricity, its surface becomes covered with the electric fluid taken from that part of the glass which it touches. When detached from the glass, this fluid flows along the wire by which the ball is suspended, this wire being also a conductor of electricity; and from this wire it passes away through the material of the stand by which the wire is supported. But a silk thread being a non-conductor of electricity, the electric fluid taken by the ball from the glass cannot escape when the ball is suspended by such a thread, and is therefore retained upon it.

(19.) If the stand to which the ball is suspended consist of a pillar of glass, the same effects will ensue, whether the ball be suspended by a conducting or a non-conducting thread; for if the ball be suspended by a metallic wire, the electric fluid received by the ball when it touches the glass will be spread over the ball and the wire; but its escape will be prevented by the glass pillar from which the wire is suspended, glass being a non-conductor.

(20.) Water, whether existing in the liquid or vaporous form, is a conductor of electricity *; and this property affects, in a very important manner, all electrical experiments. The atmosphere contains suspended in it at all times more or less aqueous vapour; and the presence of this conducting substance, mingled with the pure atmospheric air, which is a non-conductor, impairs the non-conducting quality of the latter, and facilitates the escape of electricity from all excited or electrified bodies. This is one of the reasons why electrical experiments are made with more facility, and the desired effects produced with more certainty and success, in cold and dry weather, the atmosphere then holding but little aqueous vapour suspended in it.

(21.) It also happens that, when the atmosphere is highly impregnated with vapour, more or less of this vapour is deposited in a film of moisture on the surfaces of bodies exposed to the air, more especially on surfaces which have an attraction for such vapour. When such

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* It will appear hereafter that its conducting power is of an order very inferior to that of the metals.

a coating of moisture is deposited on the surface of a non-conducting body, it impairs or destroys its non-conducting power. If, under such circumstances, glass or resin, or any other non-conductor, be excited by friction, the electricity evolved will escape by means of the conducting power of the moisture which rests upon the surface. In like manner, if pillars of glass or resin be used as supports to insulate electrified bodies, or if threads of silk be used for the same purpose to suspend electrified bodies, those substances will lose their insulating power, since the moisture deposited upon them will enable the electricity to pass away. In warm weather, therefore, and, in general, at any time when the atmosphere is strongly impregnated with vapour, the success of electrical experiments can only be insured by keeping the insulating supports dry, by constantly rubbing them with a dry warm cloth, which is itself a non-conductor. A silk handkerchief is very fit for this purpose.

(22.) The distribution of all bodies into two great classes of conductors and non-conductors, like most other systematic classifications in physical science, is not in strict conformity with the natural properties of material substances; and though such a distinction is useful and necessary, it must be adopted subject to a clear knowledge of the restrictions under which only it can be applied. Few bodies can be found which, in a strict sense, belong to either of the specified classes; and many exist which present nearly equal claims to be placed under either of them. There is, in fact, no substance whose surface is strictly impassable by the electric fluid, though there are many which offer such obstruction to its propagation over them, that, in a practical sense, they may be regarded as non-conductors. It is equally impossible to find any body whose surface offers so free a passage to the electric fluid, that under no conceivable circumstance is any the least obstruction discoverable; but there are many which offer an obstruction so extremely small in amount, that they may be, and are, regarded as practically perfect conductors. Finally, there are many substances which possess the conducting power so imperfectly, that it seems doubtful to which class they should most properly be assigned. There is, in a word, a progression of degrees in which the conducting power is found in bodies; and the various substances in nature might be tabulated or arranged in a series, beginning with that substance over which electricity passes most freely, proceeding through gradations to those substances which offer such obstruction to its passage as scarcely to be considered as conductors, and from these through the catalogue of bodies offering more and more obstruction to its transmission, until we arrive at that substance which approaches nearest to an absolute non-conductor. In the formation of such a series, however, much difficulty is found, owing partly to the absence of any precise measure of the conducting power of bodies, and partly to the fact that the conducting power of the same body at different times is subject to variations, proceeding from causes external to it; such as its hygrometric state, or its temperature.

(23.) Of all known substances, those which offer least obstruction to the passage of electricity are the metals. These bodies all appear to transmit common electricity without sensible obstruction: but, from experiments made with galvanic electricity, there is reason to think that even the metals are permeable in different degrees by the electric fluid.

(24.) Mr. Singer, so well known for his investigations in electricity, observes, that a tendency of the electric fluid to pass through good conductors offers a measure of their conducting power: for if various substances of the same length and magnitude are used simultaneously to connect an electrified conductor with one not electrified, that through which the fluid passes in preference to the others is the best conductor; or if they are placed in succession, that which conveys the charge most completely may be considered the most perfect. Metals, although the most perfect of known conductors, offer some slight resistance to the transmission of electricity; and a charge will even prefer a short passage through air to a current of twenty or thirty feet along thin wire.

(25.) The bodies composing the following series are arranged in the order in which experiment has shown them to possess the conducting power; the most perfect conductors standing at the head, and the most perfect non-conductor at the conclusion, of the series. The black line divides the most imperfect conductors from the most imperfect non-conductors: but, according to what has been already explained, the position of this line is in a great measure arbitrary, and the exact relative position of many of the substances composing the series is, as yet, unascertained: —

All the metals.
Well-burnt charcoal.
Plumbago.
Concentrated acids.
Powdered charcoal.
Dilute acids.
Saline solutions.
Metallic ores.
Animal fluids.
Sea water.
Spring water.
Rain water.
Ice above 13° Fahrenheit.
Snow.
Living vegetables.
Living animals.
Flame.
Smoke.
Steam.
Salts soluble in water.
Rarefied air.
Vapour of alcohol.
Vapour of ether.
Moist earths and stones.
Powdered glass.
Flowers of sulphur.

Dry metallic oxydes.
Oils, the heaviest the best.

Ashes of vegetable bodies.
Ashes of animal bodies.
Many transparent crystals, dry.
Ice below 13° Fahrenheit.
Phosphorus.
Lime.
Dry chalk.
Native carbonate of barytes.
Lycopodium.
Caoutchouc.
Camphor.
Some siliceous and argillaceous stones.
Dry marble.
Porcelain.
Dry vegetable bodies.
Baked wood.
Dry gases and air.
Leather.
Parchment.
Dry paper.
Feathers.
Hair. Wool.
Dyed silk.
Bleached silk.
Raw silk.
Transparent gems.
Diamond.
Mice.
All vitrifications.
Glass.
Jet.
Wax.
Sulphur.
Resins.
Amber.
Gum-lac.

(26.) According to the experiments of M. Achard, of Berlin, ice whose temperature is below 13° Fahr. is a non-conductor, though at all higher temperatures it is a conductor. That philosopher experimented on a rod of ice two feet long and two inches in diameter, and found that at 18° Fahr. it became an imperfect conductor, and that at 13° it ceased to have any discoverable conducting power whatever.

Since the best test of a non-conductor is to ascertain whether electricity can be excited on its surface so as to remain on it, M. Achard, having frozen some water so as to exclude all air-bubbles from it, formed it into a spheroid, and mounted it on an axis. When the temperature of this was reduced below 13°, he was able to excite upon it a very high degree of electricity by the ordinary process.

(27.) It is doubtful whether rarefied air should occupy a place among conducting bodies, for the manner in which it admits the motion of electricity is probably very different from that in which other conducting substances exert that power. It will hereafter appear that the electric fluid is retained on the surfaces of electrified bodies by the atmospheric pressure, and that when its tension exceeds this pressure it escapes spontaneously. Whatever, therefore, be the intensity of the electric fluid on any electrified body, if the atmosphere surrounding it is so rarefied that its pressure shall be less than that tension, the electricity must escape by its self-expansive power; and, in this sense, the surrounding air thus rarefied may be regarded as a conductor. Various experiments have been made to ascertain whether a vacuum is or is not a non-conductor; and, although the question cannot be considered as finally settled, there appears every reason from analogy to consider it a perfect conductor.

(28.) In conformity with the usage of all writers on this branch of physics, we have adopted, and shall continue to use, the term *conducting power* to express that quality of bodies in virtue of which they afford a free passage to electricity. It were, however, to be wished that this property had been designated by some term which would more correctly express what appears, from observation and experiment, to be its nature. Experiment seems to prove that the particles of bodies have no peculiar affinity for the free electric fluid, and they neither attract nor repel it. So far, therefore, as the phrase conducting power implies an *active* quality in relation to that fluid, it does not correctly express the property to which it is applied. A conductor exercises no action on the electric fluid, and is merely characterised by the negative or passive condition of offering no obstruction to its motion. The electric fluid, being self-expansive, has a natural tendency to diffuse itself into the surrounding space; and when, in virtue of this elasticity, it passes from the surface of one conductor to the surface of another, the effect is analogous to that which takes place when a vessel filled with common air is put into communication with another vessel in which there is a vacuum. The air, by its elasticity, expands and diffuses itself through the dimensions of the two vessels, having before been confined to one of them. What the vacuum is to a vessel filled with air, a conductor in its natural state is to an electrified conductor. We do not wish, however, to be understood to state that, when an electrified conductor is brought into contact with another conductor not electrified, the electric fluid diffuses itself over both conductors *according to the same law* as air would distribute itself between the two receivers just referred to. It *does*, however, diffuse itself over both conductors according to its own peculiar laws.

(29.) The physical condition which confers on bodies this conducting power has been a subject of fruitless inquiry among electricians. All that is known respecting it is, that the conducting quality depends partly, if not altogether, on the peculiar arrangement of the particles of bodies, and is not dependent on the particles themselves. It has been ascertained, that all bodies become conductors in a state of solution.

It is natural to inquire whether any relation exists between the power of conducting electricity and other imponderable physical influences, such as light and heat. There is, however, one obvious distinction to be observed between the manner in which light and heat are transmitted through bodies, and that in which electricity is transmitted by them. If a body be capable of conducting or transmitting light, that fluid will pass through its solid dimensions; thus glass, water, air, and other transparent bodies, allow light to pass through them; in other words, they are conductors of light, while the metals generally, and other opaque substances, refuse to admit light through their dimensions, and either reflect it from their surfaces or absorb it upon them. The metals in general are free conductors of heat: if one end of a metallic bar be heated, the heat soon passes through all its dimensions, and the temperature of the other end rises. But, on the other hand, glass and water, which are such perfect conductors of light, scarcely possess the power of conducting heat at all: one end of a rod of glass may be rendered white hot, while no sensible elevation of temperature takes place at the other end.

Electricity, however, is transmitted or excited not through the interior dimensions of bodies, but only on their surfaces; and the conducting power, therefore, belongs solely to the surface. No relation exists between the conductors of heat or light and those of electricity. Glass, which is almost a perfect conductor of light, is a non-conductor of heat, and also of electricity. Sealing-wax, which is an opaque substance, and therefore a non-conductor of light, is likewise a non-conductor of heat and electricity. The metals, on the other hand, which are non-conductors of light, are conductors of both heat and electricity. Water is a conductor of electricity and light, but a non-conductor of heat.

Neither does there appear to exist any general or constant relation between the conducting power of bodies and the state of cohesion of their particles. The metals, and vitreous and resinous bodies, when in the solid state, manifest an active principle of cohesion among their particles; but the metals are good conductors, while glass, gum, and resin are non-conductors. Most liquids are conductors, but possess this quality in very different degrees. The oils are very imperfect conductors. Wax and tallow, when cold, and therefore solid, are very bad conductors, but when melted they are comparatively good ones. The conducting power is found to exist in bodies having the most opposite physical characters: the flame of alcohol is a conductor, and so is ice. At common temperatures, the bodies over which electricity passes have no sensible effect upon it. The same electric spark will be derived from electricity transmitted by an iron conductor, whether the iron is at the temperature of melting ice or red hot. The same spark is obtained if the electric fluid be conducted by ice itself.

(30.) The non-conducting quality of atmospheric air is shared by all gases when in a dry state; but, besides the insulating property which these bodies possess in virtue of the absence of the conducting power, they all, in common with atmospheric air, owe a great part of their insulating power to the mechanical pressure which they excite upon the surface of electrified bodies. It appears that this pressure is the chief agent by which the electricity is retained upon such bodies. This fact may be established by experiment in the following manner: — Let a metallic ball, suspended by a silken thread, be electrified, and placed under the receiver of an air-pump. Let the air under the receiver be then rarefied by the action of the pump: the ball will lose its electricity by degrees, according as it is relieved from the pressure of the surrounding air by gradual rarefication.

If the same experiment be made with a ball of glass, of equal magnitude, similarly suspended, and also electrified by previous friction, it will be found that this ball will also lose its electricity when the air in the receiver is rarefied; but it will not lose it so rapidly as the metallic ball.

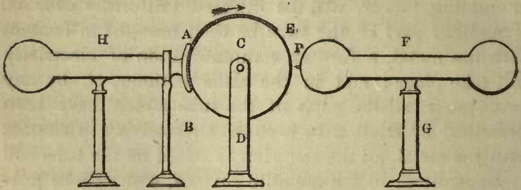
(31.) The conducting power of the metals is of great use in the construction and adaptation of apparatus for experimental investigations in electricity. A body having an extensive metallic surface, placed on an insulating support such as a pillar of glass or resin, or suspended by insulating cords such as threads of silk, may be regarded as a reservoir or vessel in which electricity may be collected and retained for experimental purposes. It is true that, after the lapse of a certain time, it will be dissipated; but it can always be retained for a time sufficient for the purposes of experimental inquiry.

It is very easy to comprehend how electricity may be accumulated on such a body. Let a glass tube be electrified by friction, and brought in contact with an insulated metallic surface. The electricity upon the tube at and immediately around the point of contact will pass to the metallic surface, and, in virtue of its conducting power, will be diffused uniformly over it. If another part of the tube be then brought in contact with the metal, a further communication of electricity will take place; and in the same manner, if, by any contrivance, all the parts of the tube which have been electrified by friction be brought successively in contact with the metal, all the electricity excited on the tube will be transmitted to the metallic surface, and will be uniformly diffused over it. The tube may then again be excited by friction, and the electricity with which it is charged may, in like manner, be communicated to the metallic surface. By continuing this process, the insulated metallic surface may be charged with any quantity of accumulated electricity.

But it is evident that the mechanical labour of exciting the tube in the manner already described, by holding it in one hand, and the cloth to rub it in the other, would be considerable, and the process would be otherwise inconvenient. If the tube were mounted so as to be capable of revolving on an axis, while the cloth were held against it by a fixed support, the manual labour would consist merely in giving a motion of rotation to the tube, which might be accomplished by a small handle or winch. The tube would be thus made to revolve by a manual operation similar to that by which a barrel-organ is worked.

Such is, in fact, with certain modifications and additions, the ELECTRICAL MACHINE, a detailed description of which we shall give hereafter; but it will be convenient at present to render the general principle and purpose of such a machine understood. Instead of a tube, a cylinder of glass, of considerable magnitude, is mounted on bearings placed at the extremities of its geometrical axis, and is made to revolve on that axis by a winch or handle attached at the extremity, so as to move outside the supports of the cylinder. A transverse vertical section of such a cylinder is represented at C (*fig. 3.*), supported at the

Fig. 3.



ends of its axis by uprights, D. The cylinder is kept moving, in the direction of the arrow, by the winch already referred to. A cushion, A, is supported by a pillar, B, and pressed by a spring against the glass cylinder. A cloth of the proper material for exciting electricity is attached to the cushion, and carried round part of the cylinder terminating at E. As the cylinder revolves, its surface becomes covered with electricity, excited by friction with the cloth A E; and if the apparatus were limited to such a cylinder, it would soon be covered with all the electricity it is capable of retaining.

This cessation of the production of electricity is provided against by a conductor, F. This is a body with a metallic suface in the form of a cylinder of considerable length, having extremities which are segments of spheres greater than a hemisphere; and it is supported on a pillar G of glass, or other non-conducting substance. From the end of the conductor, which is presented to the side of the cylinder, a horizontal row of metallic points project, one of which is represented at P. The height of the pillar G is so adjusted, that these points shall be at the same level as the axis of the cylinder, and they are so disposed as to extend throughout the length of the cylinder.

The conductor is so placed that these points shall be very nearly in contact with the glass. While any portion of the cylinder's surface is moved from the rubber A to the point E, electricity is excited upon it by the friction of the cloth. As it descends to P, it gives up this electricity to the metallic points, which have an attraction for it, the nature of which will be explained hereafter; and from these points it passes to the conductor F, over the surface of which it diffuses itself. This process may be continued until the conductor has received from the cylinder all the electricity which the pressure of the air surrounding it is capable of retaining on its surface.

If it be desired to collect a still greater quantity of electricity, it is only necessary to provide two or more insulated conductors, similar to F, which, being put successively in communication with the cylinder C, may be similarly charged; or if two or more of these insulated conductors be connected together by metallic chains or wires, which will give free passage to the electricity from one to the other, they may be all simultaneously charged by the cylinder C. In fact, they may be then regarded as one continued conductor.

Such is the general principle of the ELECTRICAL MACHINE, by means of which electricity is produced and accumulated at pleasure, for the purpose of experimental investigation. In the details of the construction of these machines, there are, however, many other principles brought into operation, depending on more complicated phenomena, which will be explained hereafter. The description of the actual form and construction, therefore, of electrical machines, as now used, must be postponed until the phenomena on which they depend have been explained. Meanwhile, it will be apparent, from what has been above stated, that, by the aid of apparatus such as we have here described, electricity may be evolved and accumulated, and, when so accumulated, may be transferred from place to place by insulated conductors, or may be made to pass from one conducting body to another by wires, chains, or cords of any conducting substance.

(32.) When an electrified conductor is touched by the finger, it instantly loses all its electricity. Where, it may be asked, does this electricity escape to? It is easy to show that it passes through the body of the person touching the conductor, and from his body to the earth.

To demonstrate this, let us first suppose that a pith ball, suspended by a non-conducting thread, is charged with electricity. We have seen that if it be touched by the finger it will immediately lose all its electricity. But, instead of being touched by the finger, let it be brought in contact with another pith ball, of ten times its diameter, also suspended by a non-conducting thread. It will be found that the smaller ball, after the contact, will have retained but a small portion of its electricity. In fact, the greater ball, having a diameter ten times greater, has a surface a hundred times greater, than the smaller one; and the electricity which, before the contact, was confined to the surface of the smaller ball, is diffused, after the contact, by the conducting power of the balls over the surface of both. The greater ball takes a portion of it nearly a hundred times more than is left on the smaller ball, and the electricity remaining on the smaller ball is therefore nearly a hundred times more feeble than it was before the contact. It is evident, that the degree in which the electricity on the smaller ball is diminished by such means will depend on the proportion of the surfaces of the two balls; and that, by augmenting the magnitude of the greater, the quantity of electricity left upon the lesser will become insensible.

If, then, an electrified conductor be taken to represent the smaller ball, and the whole globe of the earth the greater, it will be easily perceived that, when such a conductor is made to communicate with the earth by any conducting substance, such as a metallic wire or chain, or the human body, the electricity which was before accumulated on the insulated conductor will be shared between it and the whole surface of the earth; and as its surface, however extensive it may be, must be infinitely small compared with that of the earth, the electricity remaining on the conductor must be proportionately small compared with what it has lost. In fact, the quantity remaining on it is inappreciable, and the conductor may be considered as restored to its natural state.

(32.) As all bodies temporarily electrified must, in this manner, give up their electricity to the earth, the moment that the means taken to insulate them are removed, or whenever they are touched by any conducting substance, or even by the conducting power of the aqueous vapour suspended in the air, the earth is called the *common reservoir* of electricity. All free electricity, wherever and however confined and accumulated, must return to it.

The conducting power of the human body, as well as the use of insulators in electrical investigations, may be illustrated by the following interesting experiment.

If a metallic body or other conductor, insulated by standing on supports of glass, be charged with electricity, this electricity may be drawn off and transmitted to the earth by presenting to the body so insulated any conducting body which communicates with the earth. If the extremity of such conductor consists of a knob or ball of metal, when brought near the insulated conductor the electricity will pass from the latter to the former, accompanied by a bright spark distinctly visible and a cracking noise; the brightness of the one and the loudness of the other being proportionate to the quantity of electricity accumulated in the insulated conductor. As the animal body is known to be a conducting substance there is no reason why a *man* might not be used, instead of the insulated conductor, in this experiment. Let a stool with glass legs be provided, on which a man shall stand: electricity may be communicated to his body thus placed. The electricity thus imparted to him, being prevented from escaping by the non-conducting power of the legs of the stool, will be retained in his body. When a sufficient quantity is thus accumulated in his person, a knob of metal, communicating by a chain or wire with the earth, being brought near some part of his person,—his head, for example,—a spark of electricity, accompanied by a noise like that of a small explosion, will pass from his head to the ball. (INTROD. (16.))

CHAP. II.

OPPOSITE ELECTRICITIES.

(34.) It has been shown that two pith balls, suspended in contact by non-conducting threads, when electrified repel each other. This is a general law. All bodies whatever, when electrified by the contact of the same excited surface, repel each other, and continue to exercise such reciprocal repulsion until they are deprived of the electricity diffused upon them. This repulsion is manifested not only between bodies like the two pith balls, which have derived their electricity from contact with the same excited surface, but also between a body excited by friction and another which has been electrified by contact with it. When a glass tube has been electrified by friction with a woollen cloth, and has imparted a portion of its electricity to a pith ball suspended by a non-conducting thread, it will repel that ball, as has been already shown; and the reciprocity of this effect is only prevented from being visible by the comparative inertia of the glass. The repulsive force which produces a visible displacement on so light a mass of matter as the pith ball, when shared by the component parts of so much heavier a mass as the glass tube, can produce no sensible effect. If, however, a hollow glass ball, equal in weight to the pith ball, were electrified by friction, and suspended similarly to the pith ball, the same reciprocal repulsion would be produced between it and the pith ball as was manifested between the two pith balls electrified by contact with the glass tube.

(35.) It will be observed that the pith balls, which manifest a mutual repulsion, have in this case been both electrified by the same body. As, however, it has appeared that a great variety of substances are capable of being excited by friction, it is natural to inquire whether the electrical state to which they are brought is the same in all, or, if not, in what respects it differs in different bodies. For this purpose, let a stick of sealing-wax and a piece of amber be excited by the friction of the same woollen cloth; and let two pith balls, suspended on different stands, be electrified by contact with them. If these pith balls be then brought near each other, a mutual repulsion will ensue. The same effect would have been produced if both pith balls had been electrified by contact with the same excited body, whatever that body might be.

If, after the pith balls are restored to their natural state by being touched by the finger, one of them be electrified by sealing-wax excited by the friction of a woollen cloth, and the other by glass excited by friction with the same cloth, the same effects will not ensue. On bringing one ball near the other, instead of manifesting a mutual repulsion, they will now attract each other. It is evident, therefore, that the electricity produced by friction upon the glass has a different quality from that produced by friction upon the wax. These electricities impart a power of mutual attraction to bodies to which they are communicated; while, on the other hand, bodies both electrified by either glass or wax acquire a power of reciprocal repulsion.

To extend and vary these experiments still further, let us suppose a pith ball to be suspended by a non-conducting thread, and electrified by a glass tube excited by friction. Let a variety of substances be provided, susceptible of electrical excitation. These being electrified by friction, let them be successively presented to the pith ball electrified by the glass tube. By some of them this ball will be attracted, and by others it will be repelled. It is evident, therefore, that the electricity on the latter is contrary in its nature and effects to the electricity excited on the former.

Since this electricity excited on glass is found to repel the pith ball, to which the same electricity has been imparted, all those substances which, when excited, also repel the pith ball are said to be electrified similarly to the glass; while all those substances which have the contrary effect of attracting the pith ball, are said to possess a *contrary* kind of electricity. Vitreous substances generally are among those which produce the electricity by which the ball is repelled; while wax, amber, and resinous substances generally, are among those by which the ball is attracted. The name of *vitreous electricity* has therefore been applied to the one, and *resinous electricity* to the other. It will, however, presently appear that the actual phenomena are not in accordance with these terms; and the names *positive* and *negative* electricity have partially superseded them, — *positive* electricity being substituted for *vitreous*, and *negative* for *resinous*. These latter terms are not free from objection, taking their origin, as they do, from a theory of electricity which, being proved to be incompatible with the phenomena, has been superseded by one more adequately representing them. Both systems, however, are used by writers of the present day, and both, therefore, should be rendered familiar to the student.

Since, then, the substances are so various which produce these two electricities, and since even the same substance, as will presently appear, may produce each of them, what, it will be asked, is the test of *similar* or *different* electricities? and how is the positive or vitreous to be known from the negative or resinous?

This question is answered by the statement of the following law, to which there is no exception, and which, indeed, must be regarded as constituting the definition of similar and opposite electricities: —

(36.) *Bodies charged with similar electricities mutually repel each other; and bodies charged with opposite electricities mutually attract each other.*

(37.) *Positive, or vitreous, electricity is that which is produced upon polished glass when rubbed with a woollen* *cloth; and electricity of the contrary kind is negative, or resinous.*

(38.) It has been shown that these attractions and repulsions are transmitted without obstruction through the body of air by which the electrified bodies are surrounded, and which intervenes between them. Air, however, is not the only medium through which these attractions and repulsions act. They are likewise transmitted freely through all non-conductors, such as glass or resin.

If a pith ball, suspended by a silk thread, and electrified by a glass tube excited by friction with a woollen cloth, be placed within a glass receiver, it will be repelled when the excited glass tube is brought near the side of the receiver, in the same manner as would happen if the glass receiver were not interposed between the tube and ball. If, on the other hand, a stick of sealing-wax, excited by friction with the same woollen cloth, be brought near the side of the receiver, the pith ball, electrified by the glass, will be attracted.

(39.) The attractions and repulsions of electrified bodies are likewise transmitted through conducting bodies, such as the metals; but their effects are so modified in that case by other phenomena, which will be explained hereafter, that they are not observable.

(40.) The simple apparatus of a small pith ball, suspended by a silken thread, and electrified by glass excited by the friction of a woollen cloth, is sufficient, in all ordinary cases, to detect the presence and species of electricity on any body.

If a body produce neither attraction nor repulsion on such a ball, it is not electrified; or, at least, not sufficiently so to produce a force strong enough to overcome the rigidity of the silken string. If, however, it repels the ball, it must possess positive electricity.

The electricity upon the body under examination may be so feeble, that its attraction or repulsion shall be incapable of moving the ball through any sensible space. The sensibility of the apparatus may, under such circumstances, be augmented by using a fine thread and a lighter ball; but we shall hereafter explain the construction of instruments by which the presence of electricity is more accurately determined and measured. Such an apparatus as is described above is, in many cases, sufficiently sensible, and will serve to explain the phenomena to which we shall at present confine our attention.

(41.) When two bodies are submitted to the process of friction, there is nothing in the mechanical circumstances of the operation to lead to the supposition that any peculiar effect could be produced upon one without some corresponding effect being produced upon the other. When, therefore, glass, sealing-wax, or any other non-conductor, is electrified by friction with another substance, it is natural to infer that the substance with which it is rubbed must undergo some physical change, or acquire some quality having an analogy to that which is acquired by the body rubbed. Such an inference is rendered more probable by the circumstance that the electricity acquired by glass or resin is the same, whether the glass or resin be kept at rest and the cloth rubbed upon it, or the cloth be kept at rest and the glass or resin rubbed against it; or, finally, whether the friction be produced by motion imparted to both.

To determine this, it is only necessary to bring the cloth with which the conductor is rubbed to the test of the electrified pith ball above explained. If glass be excited by the friction of a woollen cloth, the glass will be vitreously electrified, as has been already shown, and will therefore repel the pith ball. If the woollen cloth be presented to the same pith ball, it will attract it; and we therefore infer that the woollen cloth is resinously, or negatively, electrified.

Again: let the same woollen cloth be rubbed upon a stick of sealing-wax, and the pith ball being as before positively electrified, the sealing-wax will attract it, since the latter is negatively electrified; but if the woollen cloth with which the sealing-wax has been rubbed be presented to the pith ball, repulsion will take place.

It appears, then, that the woollen cloth is capable of being electrified either positively or negatively, according as it is rubbed against the glass or the wax, and that in each case it acquires an electricity of a kind contrary to that which it imparts to the substance against which it is rubbed. If it be rubbed against glass, the glass acquires positive electricity, while the cloth acquires negative electricity. If it be rubbed against sealing-wax, the latter acquires negative electricity, and the cloth will be positively electrified.

(42.) If these experiments be carried further, it will soon become apparent that not only the substance used as a rubber is capable of acquiring either kind of electricity according to the substance against which it is rubbed, but that the same substance, when submitted to the friction of different rubbers, may be either positively or negatively electrified.

To prove this, let a tube of polished glass be rubbed first with a woollen cloth, and then with the fur of a cat. In the first case, as has already been explained, the glass will be *positively* electrified, but in the second it will be found to be *negatively* electrified. The species of electricity excited upon glass is, therefore, not always the same; but is sometimes positive and sometimes negative, according to the substance with which it has been rubbed.

If the fur of a cat, after having been rubbed on glass, be examined, it will be found to be positively electrified, while the glass is negatively electrified. The glass and cat's fur are, therefore, oppositely electrified. By continuing and varying those experiments it will be found that the electricity produced when two bodies are submitted to friction is subject to the following law: —

(43.) *The electricities excited by the mutual friction of two bodies are always of contrary kinds; one being positive, and the other negative.*

The objection against the use of the terms *vitreous* and *resinous*, to express the two opposite species of electricity, will now be apparent. These terms imply, that when vitreous bodies are excited, they are always electrified with the one species of electricity; and that when resinous bodies are excited, they are always electrified with the other. Such an hypothesis is, however, at variance with the facts which have been just demonstrated; the same body being capable of being electrified with either kind of electricity, according to the substance with which it has been rubbed.

(44.) In order to verify more extensively the above important law, that all bodies submitted to friction acquire opposite kinds of electricity, the following arrangement should be made. If the bodies under experiment be solid, it will be advantageous to form them into flat plates, the faces of which may be exposed to friction. The magnitude of the surface operated upon is thus increased, and the quantity of electricity evolved proportionably augmented. If the bodies be conductors of electricity, they should be furnished with non-conducting handles or supports, to prevent the escape of the electricity excited upon them. Whether the bodies under examination be solids, or have the form of stuffs or cloths, or are the skins of animals, they may be insulated by these means, or by being suspended by threads of silk kept well dried. When the two bodies have been submitted to friction they must be separated, and, while still insulated, presented successively to the electrified pith ball previously described. One of them will always be found to attract, and the other to repel it. A vast number of experiments have been made with a view to the discovery of the physical circumstances which determine the species of electricity which different substances acquire, but hitherto this inquiry has not been attended with satisfactory results. The following is a series of non-conducting substances, arranged in such an order that, when any one of them is rubbed against any other, that which stands first in the list becomes positively electrified, and therefore the other will be negatively electrified: —

1. Fur of a cat.
2. Polished glass.
3. Woollen cloth.
4. Feathers.
5. Wood.
6. Paper.
7. Silk.
8. Gum lac.
9. Rough glass.

Thus, if the fur of a cat be rubbed against any one of the eight substances which follow it upon the list, it will be positively electrified, while the other substances will be negatively electrified. If wood be rubbed against any of the four substances which precede it, it will be negatively electrified, while the substance against which it is rubbed will be positively electrified; but if it be rubbed against any of the four substances which follow it upon the list, it will be positively electrified, while the substance against which it is rubbed will be negatively electrified.

(45.) The species of electricity which two bodies acquire by friction is not always the same, and is sometimes influenced by circumstances apparently of an indifferent nature. For it appears by the above series (which has been deduced entirely from experiments, independently of any theory) that if a piece of polished glass be rubbed against a piece of rough glass, the former becomes positively, and the latter negatively, electrified. But there appears no reason why the polish of the surface should produce this effect. If two lengths of white silk ribbon, cut from the same piece, be rubbed one across the other, that which is rubbed transversely will become negatively electrified, while that which is rubbed longitudinally will be positively electrified. There is, however, no apparent reason why the direction of the threads forming the ribbon should affect the species of electricity it acquires. Æpinus found that a plate of copper rubbed against sulphur, and that two similar squares of glass rubbed against one another, produced electricity — that they were always oppositely electrified, but that the electricity each acquired was not always the same. The copper, when rubbed against the sulphur, was sometimes positive, and sometimes negative, the sulphur always having an electricity of an opposite kind; and the plate of glass, which was at one time positively electrified, was at another time electrified negatively; the other plate undergoing corresponding variations.

(46.) The following experiment furnishes an interesting illustration of the production of opposite electricities. Let two persons be placed upon insulating stools (that is, stools having glass legs to prevent the escape of electricity to the earth), and let one of them, holding in his hand the fur of a cat, well dried, strike the other with it two or three times. He that strikes will have his body charged with positive electricity, and he that is struck will be charged with negative electricity. This may be proved by the usual test of the electrified pith ball. The ball being positively electrified, let the first present his hand near it, and it will be repelled; but if the second present his hand towards it, it will be attracted. If a person not insulated present his finger to the face of either of them, a spark will pass from their flesh to his finger.

If either of those persons descend for a moment, he will lose all the electricity with which he is charged, which will escape to the earth. If, in performing the above experiment, one of the two persons only stand on the insulating stool, he alone will be charged with electricity, the electricity excited in the other escaping immediately to the earth. If neither of these persons be so insulated, neither will exhibit signs of electricity. The electricity will be excited in each of them as before, but, as they are not separated from the earth by any non-conducting substance, it will immediately escape.

In experiments of this kind, the fur of the cat is the most convenient substance which can be used, owing to the facility with which electricity is produced by it. If in dry weather, the hand be passed over the back of a living cat, the hairs will bristle and be attracted by the hand; and sometimes a cracking noise will be heard, and sparks observed. These latter effects, however, which are also observable with human hair, only take place in very cold weather, when the air, from its extreme dryness, becomes a good insulator. The human hair, when clean and dry, and not greased, may be electrified with great facility by friction. This is especially the case with fair hair, which is generally fine and pliable.

(47.) The opposite electricities produced by friction may be demonstrated by the electrical machine, of which the general principle has been explained. Behind the rubber or cushion A (*fig.* 3.) let a conductor, H, be placed, and let it be insulated by standing upon a glass pillar, the cushion being also insulated. When electricity has been excited by turning the glass cylinder, the glass and the cushion, in accordance with what has been explained in this chapter, acquire opposite kinds of electricity. The positive electricity produced upon the glass passes off to the conductor F, and the negative electricity produced upon the rubber passes off to the conductor H. These conductors are accordingly called, respectively, positive and negative conductors. Electricity will continue to be accumulated on each of them until as much has been collected as the atmospheric pressure is capable of retaining on their surfaces. As opposite electricities have an attraction for each other, there is a continual tendency of the negative electricity to flow towards the positive, and of the positive to flow towards the negative, conductor; and if the action of the machine were suspended, nothing would prevent the excess of electricity on each conductor from flowing to the other, and thus restoring the electrical equilibrium, and reducing the conductors to their natural state, except the non-conducting quality of the glass cylinder which stands between them.

(48.) The property of exciting electricity by friction is not confined to solids. The friction of liquids against solids and against each other produces like effects. On the top of a glass receiver let a wooden cup be attached, so that no air can pass between it and the glass. The receiver thus arranged being placed upon the plate of an air-pump, and the wooden cup being filled with mercury, let the air within the receiver be rarefied by the pump. The pressure of the external atmosphere will force the mercury through the pores of the wood, and it will fall like a shower of silver within the receiver, striking against the sides of the glass as it descends. If the electrified pith ball be brought near the side of the glass while the mercury is thus falling, it will be attracted or repelled according to the species of electricity with which the ball is charged, demonstrating that the inner surface of the glass is electrified.

(49.) If the column of mercury supported in the tube of a barometer be made to ascend and descend by alternately inclining the barometer from side to side, the friction of the mercury within the tube will be attended with the evolution of electricity; and if the experiment be made in the dark, a faint luminous appearance will be observed to follow the motion of the mercury.

(50.) Electricity may be also excited by the friction of gases against solids. If a blast of air be directed by bellows upon a plate of glass, the glass will be positively electrified, and the electricity may be detected by the usual tests.

(51.) Friction, though the most convenient and usual, is not the only, method of exciting electricity. Electricity is evolved in almost every important change of form or constitution which bodies undergo. It is evolved in the fusion of solids. Let a metallic vase be placed on insulating supports, and let melted sulphur be poured into it. When the sulphur cools and hardens, and is removed from the vessel, it will be found to be electrified, and the metal will be found to have an electricity of an opposite kind. Sometimes the sulphur in this case is positively electrified, and the metal negatively; and sometimes the contrary happens.

Various mineral substances of a crystallised structure and vitreous nature are found to be electrified when their temperature is raised to a certain point. In such cases, the two extremities of the crystal are sometimes oppositely electrified, the one being positive and the other negative. The effects, however, vary.

There are various other sources of electricity, such as chemical action, and the contact of heterogeneous substances, especially metals. As these phenomena, however, will be fully explained at the proper places in these volumes, it will not be necessary here to enter into developments on the subject.

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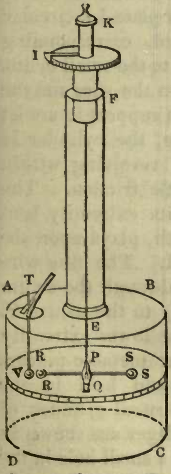
CHAP. III.

LAW OF ELECTRICAL ATTRACTION AND REPULSION.

(52.) Having ascertained the existence of the attractive and repulsive forces manifested by bodies on which electricity has been excited, or to which it has been imparted by contact with other bodies on which it has been excited, it will next be necessary to investigate the laws which govern the variation of the intensity or energy of these attractions and repulsions under the various circumstances in which the bodies affected by them may be placed. But, before commencing this inquiry, we shall explain the principle and structure of the instrument by the aid of which such forces have been measured.

Fig. 4.



The Balance of Torsion, invented and applied by Coulomb with signal success in various physical investigations, and used by him in his electrical experiments, is represented in *fig.* 4. A B C D is a glass cylinder twelve inches in diameter, and twelve inches in height; on the top is placed a glass plate A B thirteen inches in diameter, which completely covers the cylinder. In the centre of this plate a hole E is formed, in which is inserted a glass tube E F, about two feet high. In the top of this tube is inserted the balance of torsion, the parts of which are separately exhibited in *figs.* 5, 6, 7. The top of the tube E F is represented at F (*fig.* 6.). Into this passes like a telescope joint a short tube H (*fig.* 5.), to the top of which is attached a circular plate I, the edge of which is divided into 360 degrees. The tube H is permanently soldered into F. A button K carries an index L attached to a small cylinder M, to the lower end of which is attached a short rod N, at the bottom of which is a small pincers O, capable of being tightened by pressing down a ring sliding on N. These pincers hold the upper extremity of an extremely fine silver wire, kept in the vertical position by a weight hanging from it below. In the centre of the circular plate I a circular hole is formed, corresponding in magnitude to the small cylinder M. When the wire and the pincers which support it are let into this hole, the cylinder M is capable of revolving within it with a little friction. The length of the index L is such, that its extremity bent downwards at right angles to its length, plays upon the graduated edge of the circular plate I. The fine wire thus held by the pincer O, descends through the centre of the cylindrical tube E F (*fig.* 14.) to the centre P. of the great cylinder A B C D. The lower extremity of this wire is held by another similar metallic pincers P, closed by a ring like the former, and held in the vertical position by the weight of a small cylinder of metal Q. This needle and its appendages are shown in *fig.* 7. The pincers P are pierced with a small hole in the horizontal direction, through which a needle R S passes.

Fig. 5.

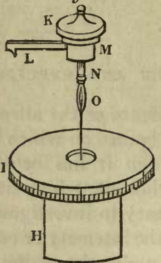


Fig. 6.

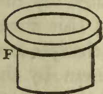
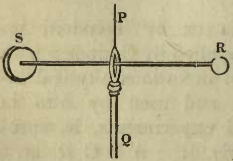


Fig. 7.



This needle is usually formed of gum lac, and is terminated at one extremity by a ball R of the pith of elder of about a quarter of an inch in diameter, and at the other end by a circular plane of paper S, steeped in turpentine, which serves as a counterpoise for the ball R, and which, by means of the resistance of the air, retards the oscillation of the needle. In the other hole T (*fig.* 4.) made in the circular top A B of the great cylinder, is inserted a small rod T V formed of gum lac terminated in a small ball V of the pith of elder. Round the great cylinder at the level of the needle S R is attached a graduated circle, by which the movements of the suspended needle S R are measured. This graduated circle is so numbered, that its degrees commence from the point which is opposite the pith ball V.

Since the tube H turns with a little friction within the tube F, the zero of the graduated circle I, or the point from which its divisions commence to be numbered, may be turned into any required position relatively to the great cylinder A B C D.

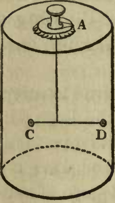
(53.) Since the small tube M turns freely within the hole formed in the centre of the circle I, the index L may be turned round, causing the piece K, the tube M, the pincers O, and the wire suspended from it, also to turn. Let us suppose that the index L is turned so as to coincide with the zero of the circle I, the wire by which the needle R S is suspended being then free from any torsion. Let the divided circle I be now turned until the pith ball R is brought opposite to the zero of the divided circle: it will be then immediately under the opening T, by which the rod of gum lac bearing the other pith ball V is let into the great cylinder. The instrument is now reduced to a state in which it is capable of measuring the force with which the balls R and V would repel each other. If the centre of the pith ball R be supposed to correspond precisely with the zero of the circle before the introduction of the pith ball V, and if the centre of the pith ball V when introduced be made to take the place of the centre of the pith ball R, it will press the latter aside, and therefore turn the needle R S through a space equal to the sum of the radii of the two balls. This will produce a very slight torsion of the wire suspending the needle R S, the reaction of which will be just sufficient to keep the two balls in contact. If either of the two balls thus in contact be electrified, the electricity will be shared by the other ball, and they will repel each other; but as the ball V is fixed, the repulsion will only take effect upon the ball R, which will separate from V, and make the needle R S move from V. R will continue thus to depart from V, twisting the wire as it turns, until the reaction of the torsion of the wire shall balance the repulsive force exercised by V upon R; R will then remain at rest at a distance from V, indicated by the division of the circle opposite to which it stands. The number of that division will also indicate the angle of torsion through which the suspending wire has been twisted, and this angle is always proportional to the reaction of the wire, or the force with which it endeavours to recover its position of rest. In this manner the force of repulsion at different distances may be measured and observed.

(54.) The extreme degree of sensibility of this instrument, and the minuteness of the quantities which it is capable of measuring, may be collected from the consideration of the dimension of the wires which were used. In the experiments which will be hereafter explained, and by which the laws of electrical attraction and repulsion were discovered, the suspending wire was 28 inches in length, and was so fine that 1 foot of its length weighed only the $\frac{1}{16}$ part of a grain. The radius of a circle described by the centre of the ball R was 4 inches; the force of torsion of this wire was found to be such, that when turned through one entire revolution, or 360 degrees, its reaction amounted to no more than the 340th part of a grain; and since the reaction of torsion is proportional to the angle of torsion, the force corresponding to the motion of the ball R through one degree of the circle was only the 122,400th part of a grain. Thus this balance so constructed was capable of dividing a single grain into 122,400 parts, and rendering each part distinctly observable.

(55.) Such a wire, on account of its extreme tenuity, and, consequently, liability to be broken by the least disturbance of the apparatus, was found to be inconvenient in experiments where the forces to be measured were not so extremely minute as to require so high a degree of sensibility. Coulomb found it therefore more convenient to employ in such cases a wire of double the diameter, and of equal length. He showed that the reaction of torsion, under like circumstances, of different wires was diminished by augmenting the length of the wire, and diminishing its diameter. This reaction, the smallness of which is the measure of the sensibility of the instrument, increases in the same proportion as the length of the wire is diminished, when its thickness remains the same; and it increases in the same proportion as the fourth power of its diameter when its length remains the same. Thus the sensibility of the instrument is in the direct proportion of the length of the suspending wire, and in the inverse proportion of the fourth power of its diameter. If, for example, the length of the wire be doubled, the sensibility of the instrument will be doubled, since the reaction produced by a given torsion will be diminished in the proportion of two to one; and if the thickness of the wire be reduced in the proportion of two to one, its length being preserved, the sensibility of the instrument will be augmented in the proportion of sixteen to one, the reaction produced by a given torsion being sixteen times less than before.

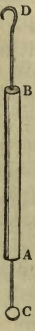
(56.) In cases where the presence of much smaller quantities of electricity was required to be detected, or their quantity estimated, Coulomb used an electrometer of a still higher degree of sensibility. From a micrometer of torsion A (*fig.* 8.), placed at the top of a cylindrical glass receiver, he suspended a single fibre of natural silk, as produced by the silkworm, four inches in length. This thread supported a small needle C D formed of gum lac, twelve lines in length, and terminated at one of its extremities by a small circular disc of gilt paper. In the apparatus employed by Coulomb, the weight of the needle and disc, taken together, did not exceed a quarter of a grain. These delicate needles are easily formed by holding a thin stick of gum lac in the flame of a lamp, and, when it is softened, drawing the ends in opposite directions. The melted part will thus be drawn into an extremely fine thread, of which the needle of the electrometer may be formed. The silk fibre, of four inches in length, by which it is suspended, has such a flexibility, that when twisted by a force acting with a leverage of one inch, its reaction after one revolution is only the 60,000th part of a grain; and consequently its reaction, when turned through one degree, would only amount to the 21,600,000th part of a grain. Thus, by this exquisite contrivance, a force is rendered actually observable amounting to less than the 20,000,000th part of a grain.

Fig. 8.



(57.) To communicate electricity to the disc, a small copper wire is surrounded by a stick of sealing-wax A B (*fig.* 9.), extending at each end beyond the extremities of the wax. At one end the wire terminates in a small gilded pith ball C, and at the other end in a hook D. The stick is introduced into the glass case of the electrometer through the opening T (*fig.* 4.), and the ball C, is placed in contact with the disc. Electricity is then communicated to the hook D, and in virtue of the conducting power of the wire it passes to the ball C, and is shared with the

Fig. 9.



disc in contact with that ball. The disc is then repelled with a force, the amount of which may be observed in the manner already explained.

The sensibility of these instruments is so great, that if, after having electrified a stick of sealing-wax by friction, it be held at a distance of three feet from the hook D, the disc will be repelled to the distance of 90° from the ball C. The manner in which this repulsion is produced by the action of an electrified body at a distance and without contact will be explained hereafter; it is only referred to at present as a proof of the extreme sensibility of this apparatus.

(58.) In the forces which are manifested between electrified bodies, the first circumstance which will attract attention is the fact that the energy of these forces is augmented as the distance between the electrified bodies is lessened. The analogies suggested by various other physical forces, whose intensities likewise increase with the diminution of the distance, and more especially the law of gravitation, by which the energy of that force increases in the same proportion as the square of the number expressing the distance between the gravitating bodies is diminished, naturally leads to the question, According to what law does the force of electrical attraction or repulsion increase as the distance between the electrified bodies is lessened? If the nature of electricity were perfectly known, this law could be deduced by general reasoning, so that the manner in which electrified bodies would comport themselves, in any position in which they might be respectively placed, could be certainly foretold. But the physical principles from which electricity arises not being known, investigation must proceed from the discovery of its laws by the direct observation and comparison of its phenomena, to the establishment of a just theory respecting its nature. To determine, therefore, the law of its variation, it is necessary to submit electrified bodies to their mutual attraction or repulsion at different distances, to measure the actual amount of that attraction or repulsion at those distances, and by comparing the results of such measurement with the distances themselves, to discover the dependence of one upon the other. This was effected by Coulomb by the aid of electrometers of torsion, such as have been described.

(59.) Let us suppose the suspended needle of the electrometer to carry at its extremity a small disc of gilt paper S (*fig.* 7.), the plane of which shall be vertical, and so placed that its edge shall be presented to the wire of suspension. Let the index of the micrometer at the top of the tube E F (*fig.* 4.) be then turned to the zero of the divided circle I (*fig.* 5.), on which it moves; also let the piece I itself, carrying with it the micrometer, be turned until the edge of the disc of gilt paper shall be presented to the zero of the divisions surrounding the case A B C D (*fig.* 4.) of the instrument. Let another similar disc of gilt paper be now introduced into the case through the opening T (*fig.* 4.), and be let down to the level of the needle, and so placed that the gilt surfaces of the two discs shall be parallel to each other and in contact. If a feeble electricity be imparted to these discs by means of the head of a pin held by a stick of sealing-wax or gum lac, the two discs, being similarly electrified, will repel each other; and that which is attached to the needle, being free, will recoil from the fixed disc under the opening T, and the needle will move through part of a revolution, producing a corresponding torsion in the suspending wire. When the reaction of this torsion becomes equal to the repulsion, the needle, after a few oscillations, will come to rest. This will necessarily take place in some position of the needle if the discs be not too strongly electrified, because while the repulsive force diminishes by the increasing distance of the moveable from the fixed disc, the reaction of torsion which resists this repulsion will be augmented.

If the index L (*fig.* 5.) be now turned in such a direction as to force the moveable disc nearer to the fixed disc, and be adjusted so as to maintain the moveable disc at rest at any required distance from the fixed disc, the force of repulsion, which must always be equal to the reaction of torsion, will be proportional to the angle of torsion, and that angle will be measured by the distance of the index L from the zero of the divisions I *added to* the distance of the moveable disc from the zero of the divisions surrounding the case A B C D (*fig.* 4.). In this manner the repulsive force corresponding to any distance of the moveable from the fixed disc *less than* that at which it first settles itself may be observed.

If the repulsive force at *greater* distance be required, then let the index L (*fig.* 5.) be turned in the opposite direction, so as to turn the moveable disc *from* the fixed disc, and when the former is brought to rest in any required position, the angle of torsion will be found by *subtracting* the distance of the index L from the zero of the divisions I (*fig.* 5.) from the distance of the moveable disc from the zero of the divisions surrounding the case A B C D (*fig.* 4.). Thus in every case the angle of torsion corresponding to any given position of the moveable disc may be found, and thereby the repulsive force at that distance may be determined.

Instead of discs of metal or gilt paper, the experiment may be made with pith balls gilt, or balls of metal.

(60.) To show the method which led Coulomb to the discovery of the law of electrical repulsion, we shall give the details of one of his experiments.

Having electrified the two discs, he found that the moveable disc, when repelled, remained at rest after it had turned through an angle of 36° from the fixed disc. The torsion therefore produced by turning the suspending wire through this angle balanced the repulsive force of the discs in this position. He now applied his hand to the index L (*fig.* 5.), and turned it round in such a direction as to move the disc upon the needle towards the fixed disc. He found that, to bring the moveable disc to a distance of 18° from the fixed disc, the index L had moved over the divided circumference I from zero to 126°. The angle of torsion, therefore, corresponding to this position of the moveable disc, was found by adding 18° to 126°, and was therefore 144°.

He now continued the motion of the index L in the same direction, so as to force the moveable disc still nearer to the fixed disc; and he found that when the distance between the discs was $8\frac{1}{2}$°, the distance between the Index L and the moveable disc or the angle of torsion was $575\frac{1}{2}$°. The results of these three experiments are exhibited in the following table:—

Distance between the Discs.	Torsion measuring the Repulsive Force.
36°	36°
18°	144°
$8\frac{1}{2}$°	$575\frac{1}{2}$°

(61). On comparing these two series of numbers, it will be observed, that those in the first column form a *decreasing* series, in which each number is nearly double that which follows it. This would be exactly the case, if the last distance were 9°. On comparing the numbers in the second column, they will be observed to be an *increasing* series, in which each number is very nearly four times that which precedes it; this would be the case exactly, if the last number were 576°; hence, it appears, that if the distances between the electrified bodies be constantly diminished in the proportion of 2 to 1, their repulsive force will be increased in the proportion of 1 to 4, or as the squares of the distances. If the law, therefore, developed in these particular experiments prevail generally, we shall arrive at the remarkable conclusion, that the same law which reigns among the great bodies of the universe, and regulates their mutual attractions, also governs the attractions and repulsions of electrified bodies.

(62.) In deducing such a conclusion from these experiments, it may be objected, that the distances between the electrified bodies have been measured, not by straight lines drawn from one to the other, but by the arcs of a circle, of which the suspending wire is the centre, and the distance from that wire to the bodies, the radius. It is, however, easy to show by geometrical calculation, that, in cases like the present, where the arcs do not exceed 36°, the distances between the bodies measured upon the arcs differ little from the distances measured in a straight line, and that the law deduced from the comparison of the arcs will therefore be applicable to the rectilinear distance.

(63.) It may also be objected that the force of electrical repulsion is exerted in a straight line joining the two electrified bodies, while the force of torsion by which this repulsion is balanced acts in the direction of a tangent to the circle described by the moveable disc; that, therefore, the two forces not acting in immediately opposite directions will not be equal; and that since the obliquity of the tangent representing the direction of the force of torsion to the straight line joining the electrified bodies is variable, the force of torsion will not even be proportional to the force of repulsion.

This objection, like the former, would be valid, if the experiment were extended to such a distance between the electrified bodies as would cause a considerable obliquity between the tangent and the line joining them; but, the present experiments being limited to angles under 36°, this obliquity is so small, that the force of torsion may, without sensible error, be taken as equal to the repulsion of the electrified bodies.

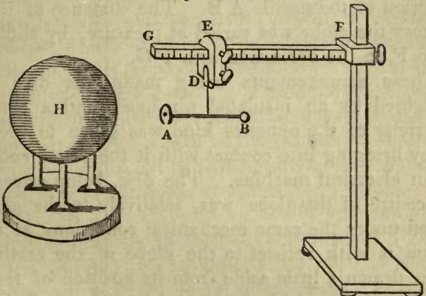
(64.) By varying the experiments, and extending them to other distances, Coulomb succeeded in establishing the universality of the law, *that bodies electrified by similar electricities repel each other with a force which diminishes in the same proportion as the square of the distances between them is increased.*

(65.) Having thus determined the law of repulsion where bodies are similarly electrified, a like inquiry was extended to the attraction of bodies oppositely electrified. An inconvenience occurs in the application of the same method of experimental inquiry to this question. When the two electrified bodies, in virtue of their mutual attraction, approach each other, the force with which they are attracted often increases faster than the force of torsion by which that attraction is resisted, so that, in spite of the resistance of torsion, the discs or balls rush into contact. It is easy to assign the mechanical conditions which will prevent this, but the inconvenience is readily obviated by extending a thread of fine silk vertically between the top and bottom of the case A B C D (*fig.* 4.), having its ends attached to them by wax. This thread should be placed near the fixed disc, and in the commencement of the experiments the needle may be placed in contact with it. When the two discs are oppositely electrified, the moveable disc may be forced from the fixed disc by turning the index L in a direction contrary to that in which it was moved in former experiments. By such means, the angles of torsion, corresponding to any distances of the electrified bodies within these limits, which will allow of the arcs being taken to represent the distances, may be observed. And by experiments thus conducted, it was found that electrical attractions were governed by the same law as electrical repulsions, and that their energy diminished in the same proportion as the square of the distance between the electrified bodies was increased.

(66.) Besides this method of determining the law of electrical forces, Coulomb also applied a method of inquiry similar in principle to that by which the variations of the force of gravity have been determined on different parts of the earth's surface. When a pendulous body is at rest, its centre of gravity must be placed in a straight line, joining its point of suspension with the centre of the earth by which it is attracted. If it be drawn from this position, and liberated, it will fall back, and with the momentum acquired in its descent, it will swing to the opposite side, and will thus continue to vibrate alternately from side to side. The rate of its vibration will be more or less rapid, according to the force with which it is attracted; and it is demonstrated in mechanics, that the energy of the force with which the pendulum is attracted will be diminished in the same proportion as the square of the time occupied by a given number of vibrations of the pendulum is increased. Thus, if in one place the pendulum were found to make ten vibrations in forty seconds, and in another it made ten vibrations in twenty seconds, then the force which attracts it in the latter case would be greater than that which attracts it in the former case, in the proportion of the square of forty to the square of twenty, or, what is the same, of the square of two to one.

This principle was applied in the following manner by Coulomb. A needle of gum lac, A B (*fig.* 10.), fifteen or sixteen lines in length, carried at one extremity a small disc of gilt paper, and was suspended by a single filament of raw silk seven or eight inches in length. The upper end of this thread was fastened to a slip of wood D, well dried in the oven, and coated

Fig. 10.



with a varnish of gum lac, by the non-conducting power of which, and of the needle itself, the disc A was perfectly insulated. The slip of wood D supporting the silk was inserted in a frame E, capable of sliding on a horizontal rod F G, to which it could be fastened by adjusting screws. The flexibility of the thread by which the needle was suspended was such, that a force equal to the 120,000th part of a grain, applied to the extremity of the needle, was sufficient to turn it one entire revolution. After having left the apparatus thus arranged standing for several days, in order to give time to the silk to untwist itself perfectly, the re-action of torsion for several degrees on either side of its position of equilibrium might be regarded as altogether insensible.

A sphere H of wood, one foot in diameter, was coated with tin-foil, and supported on three thin legs of gum lac, by which it was insulated; this sphere was placed at any required distance from the needle, in such a position that its centre stood precisely in the direction of the needle A B. The distance of the diso A from the globe was varied at pleasure, by sliding the piece F on the horizontal arm F G.

These arrangements being made, the disc A was electrified by an insulated pin-head, and a charge of electricity of the opposite kind was given to the globe H, by bringing into contact with it the prime conductor of an electrical machine. The disc, being attracted to the centre of the globe was, relatively to the globe H, placed under the same mechanical conditions as a pendulum is with respect to the globe of the earth; and when drawn a little aside from its position of rest, and disengaged, it would therefore be made to vibrate like a common pendulum, and the rate of its vibration would become an indication of the force with which it is attracted.

In the experiments made by Coulomb, he observed the time by a seconds watch, in which the pendulum performed a given number of oscillations.

When the disc A was placed at nine inches from the centre of the globe H, it vibrated fifteen times in twenty seconds. When the distance was increased to eighteen inches, it vibrated fifteen times in forty seconds; and when the distance was further increased to twenty-four inches, it vibrated fifteen times in sixty seconds.

In considering these experiments, it is necessary to observe that the globe, in consequence of its geometrical form, and of the uniform diffusion of electricity over its surface, attracts the disc A in the same manner as if all the attracting matter were collected at its centre. This is a principle which is demonstrated in mechanics. It must also be observed, that although, strictly speaking, the different points of the surface of the disc A, in any given position of the disc, are at different distances from the centre of the globe, yet the disc is so small, and the range of its vibration so limited, compared with its distance from the centre of the globe, that the change of distance arising from these causes may be disregarded. The attractive force of the globe, therefore, on every point of the disc, and in every position of it, may be regarded as invariable. These circumstances render the pendulum A in all respects analogous to a common pendulum attracted by the earth. The formula which expresses the relation between the attracting force, the time of vibration, and the length of the pendulum in the one case, will, therefore, be equally applicable to the other.

Let L then express the length of the pendulum; let T express the time occupied by one of its oscillations, and let E express the attraction exerted upon it by the globe H. Finally, let π express the ratio of the circumference of a circle to its diameter or the number 3·1415. Then, by the principles established in mechanics, we shall have, —

$$\overset{2}{\mathrm{T}}\,\mathrm{E}=\overset{2}{\pi}\,\mathrm{L}$$

$$\mathrm{E}=\frac{\overset{2}{\pi}\,\mathrm{L}}{\mathrm{T}^{2}}$$

Thus the force will always be proportional to the length of the pendulum divided by the square of the time of one of its oscillations; but, as in the present case, the length of the pendulum is the same in all the experiments, the attracting force will increase in the same proportion as the square of the time of one vibration is diminished. Now, the time of a single vibration is proportional to the time of any given number of vibrations, and consequently it follows that the energy of the attractive force will diminish in the same proportion as the square of the time taken to make any given number of vibrations increases. If the attractive force diminish in the same proportion as the square of the distance increases, then it is evident that the variation of the distance would be proportional to the variation of the time taken to make a given number of vibrations; and if this correspondence be found to exist between the variation of the distance and the variation of the time of vibration, it will supply a demonstration of the law which establishes the relation between the energy of the attraction and the distances of the electrified bodies.

In the three experiments which have just been described, the distances are proportional to the numbers 3, 6, and 8, while the times of the vibrations are proportional to the numbers 3, 6, and 9. There is, therefore, in the last of the three experiments a departure from the law to be established. The actual time taken to make fifteen vibrations, at the distance of twenty-four inches, was sixty seconds; whereas, if the attraction rigorously diminished as the square of the distance increased, fifteen vibrations ought to have been made in fifty-four seconds. The rate of the pendulum being slower than it ought to be, is an indication (supposing the law to be true) that the electrical attraction at the last distance is more feeble than it ought to be. But this is only what might have been anticipated, for Coulomb found by other experiments, made on the same day, that an electrified body lost by dissipation in the air about a fortieth part of its attractive power per minute.

Now, between the first and third of the above experiments, there elapsed an interval of four minutes, in which time the globe H would lose a tenth of its whole attractive power. If a correction be made corresponding to this loss of electricity, the result of the last experiment will be found in sufficiently near accordance with the law of attraction already established by means of experiments made with the electrometer. This method of the electrical pendulum will equally afford an experimental proof of the law of electrical repulsion. The method of experimentising will be the same, the disc A being, however, turned in the opposite direction, and the needle being placed so that A and B shall interchange places.

(67.) By means of the law of electrical attraction and repulsion the energies of the attraction or repulsion of two electrified bodies can always be found for any distance whatever, when its energy has been observed at any known distance; for let F′ be its energy observed by experiment at the known distance D′, and let it be required to calculate its force F at any other distance D; since the force increases as the square of the distance diminishes, we shall have the following proportion: —

$$F : F' :: D'^2 : D^2$$

from which the following formula follows: —

$$F = F' \frac{D'^2}{D^2}$$

To find, therefore, the force at the distance D, multiply the observed force by the square of the distance at which it is observed, and divide the product by the square of the distance at which the energy of the force is sought.

As the forces are measured by the torsion whose reaction holds them in equilibrium, the angles which measure the torsion may always be taken to represent the forces in such calculations. It may therefore be assumed in the use of the electrometer of torsion, that the angle of torsion increases in the same proportion as the square of the distance between the electrified bodies diminishes.

(68.) By such means, the whole amount of the attractive or repulsive force of two electrified bodies placed at any given distance from each other, may be determined. But, as both bodies unite in contributing to the production of this effect, it still remains to inquire what proportion of the total attraction thus determined is due to each of them. We shall arrive at the solution of the problem if we can increase or diminish in any known proportion the quantity of electricity on either of the bodies, and then observe the change in the attractive or repulsive force thus produced. Now, it is easy to take away from either of those electrified bodies half of its electricity. To effect this, it is only necessary to bring it into contact with another conducting body of the same magnitude, form, and nature, and similarly insulated. Thus, if an electrified gilt pith ball, of a certain magnitude, being insulated, be touched by an equal gilt pith ball, also insulated, but not previously electrified, then the electricity will be shared equally between the two balls ; and when they are separated, the first will possess exactly half its former quantity of electricity. By repeating the same process, the electricity upon the first ball may be reduced to a fourth or an eighth of its electricity.

This equal partition of electricity may be verified experimentally in the following manner : — In the electrometer of torsion, let a small pith ball be attached to the end of the needle, and another of equal magnitude be introduced at the opening T, and placed in contact with it. The balls being electrified by the head of a pin, let us suppose they are repulsed to a distance of 48°, and that, by turning the thread of suspension, the moveable ball is forced back to the distance of 28° ; and let the angle of torsion necessary to keep it at this distance be 148°. The needle being stationary, let the fixed ball be touched by another ball exactly equal and similar, and similarly insulated. After the ball, which has just touched it, is withdrawn, the moveable ball will approach it in consequence of the diminished repulsion, and to restore the moveable ball to its former distance of 28° from the fixed ball, it will be necessary to untwist the thread of suspension by turning the index L of the micrometer. When the index is so adjusted that the moveable ball remains at rest, the angle of torsion will be found to be a little less than 74°. It would be exactly 74°, being the half of its former value, 148°, but for the small quantity of electricity dissipated by contact with the air in the interval between the two experiments.

(69.) By the same kind of experiment, varied by changing the quantities of electricity and the distances at which the moveable ball is brought to rest, a similar result may be obtained; and the same effect is produced, whatever be the form of the bodies used, provided they be such, that, in the calculation of their mutual attraction, they may be regarded as points. Coulomb substituted for the fixed ball an iron disc, ten lines in diameter, keeping the pith ball attached to the needle. He electrified these two bodies by the head of a pin, and a repulsion was produced, such that, to keep the moveable ball at 30° from the fixed ball, a torsion of 140° was necessary. He then touched the disc of iron by another of the same diameter, after which he untwisted the wire until the moveable ball was again brought to rest at 30° from the iron disc. The angle of torsion was then found to be 70°, or half its former amount.

These and similar experiments lead to the conclusion that the diffusion of electricity on such conducting bodies brought in contact with each other depends only upon the dimensions of the bodies, and is entirely independent of the substance out of which they are formed. Whether an electrified pith ball be touched by another pith ball of equal magnitude, or by a metallic ball, or in fine, by a ball of equal magnitude formed of any conducting substance, it will equally lose half its electricity, and the effect will be the same, whether the ball which touches it be solid or hollow.

(70.) It appears, therefore, that between the electricity which is diffused over a conductor and the matter composing that conductor, there exists no peculiar attraction analogous to chemical affinity which would give the electricity a greater hold on one kind of matter than on another; for, were it so, it would be found that, when balls of equal magnitude, but of different materials, one being electrified, the other not, and both being insulated, are brought into contact, the electricity would not be equally diffused over them, but would collect in greater quantity on that for which it would have the stronger affinity. It may also be inferred that the internal dimensions of a body have no effect on its conducting power, since, whether a ball be solid or hollow, it will take the same quantity of electricity from an electrified body, with which it is brought in contact.

(71.) It appears, also, from the above experiments, that the mutual attraction or repulsion of each of two electrified bodies depends conjointly on the quantity of electricity on each of them. Thus, if the quantity of electricity on either be doubled, or halved, or augmented, or diminished in any other proportion, then their mutual attraction or repulsion will be augmented or diminished in the same proportion. If the quantity of electricity on one be double, while on the other it be halved, then their mutual attraction or repulsion would remain the same, and, in general, their attraction or repulsion at a given distance will be found by multiplying together the numbers expressing the quantities of electricity upon them respectively.

By combining this law with that which expresses the variation of the electrical force depending on the change of distance of the electrified bodies, we arrive at the following general law: —

The mutual attraction or repulsion of two electrified *bodies is directly proportional to the quantity of electricity on the one, multiplied by the quantity of electricity on the other, and inversely proportional to the square of the distance between them.*

If R express the quantity of electricity on one of two electrified bodies, and R′ the quantity of the other, then that mutual attraction or repulsion at any distance D will be expressed by the formula $\frac{RR'}{D^2}$, which is nothing more than the above law expressed in mathematical symbols.

It is remarkable, that this law is in all respects identical with that which governs the mutual gravitation of masses of matter. Thus the mutual attraction is in the direct proportion of the product of their masses, and the inverse proportion of the square of their distances.

CHAP. IV.

DISSIPATION OF ELECTRICITY.

(72.) The law determined in the last chapter, by which the intensity of electrical attraction and repulsion varies with the variation of distance, is only observed so long as the electrical state of the bodies between which these forces are exhibited remains unaltered. But in all cases where such experiments are made, the electricity diffused over the bodies is exposed to continual diminution, being dissipated partly by the contact of the surrounding atmosphere, and partly by the imperfect insulation afforded by the supports. In order, therefore, to deduce exact conclusions, it is necessary to know the extent to which, and the law according to which, electricity is dissipated or lost during the experiment.

(73.) When an insulated conductor has been electrified, the electricity has a tendency to escape from it to its insulating supports, and from these last to the earth. Although, in practice, certain substances are usually called insulators, or non-conductors, because they afford a great obstruction to the passage of electricity, yet, in an absolute sense, there is no substance in nature which does not allow electricity to be propagated upon its surface in a greater or less degree. Glass, sealing-wax, and gum lac are bad conductors, especially the last, and offer a great obstruction to the transmission of the electric influence; but still they do transmit it, and even in a sensible degree. To render this manifest, let the end of a rod formed of any of these substances be held in contact for some time with the conductor of an electrical machine, the machine being kept in operation. After withdrawing it from the conductor, let the same extremity be presented to the needle of Coulomb's electrometer, and it will be found to be charged with the electricity of the conductor. It may be objected, that in this case the electricity has been imparted to it by immediate contact with the electrified surface of the conductor, and that there is no evidence of the electric fluid moving along its surface, and, therefore, that there is no proof of any conducting power. If, however, a small piece be cut from the end of the rod which was in contact with the conductor, and the rod be then presented to the electrometer, the side of the rod contiguous to the extremity from which the piece was cut will be found to be electrified, but with less force than the extremity itself which was in contact with the conductor. In the same manner, if slice after slice be cut from the rod, and the state of its sides examined with the electrometer, it will be found that the sides, through a certain length of the rod, are electrified with a continually decreasing intensity.

(74.) The effect which is thus rendered manifest is produced in a similar manner upon the supports by which electrified conductors are insulated. The electricity upon them is gradually absorbed by the insulating supports along which it slowly, but continually, steals. If the length of these supports be less than the distance through which the electricity can force its way, then there will be a constant and slow escape of the electricity from the conductor to the earth; but even if the support be too long to allow of this, there will still be a continual escape of electricity to the insulating support so long as the latter continues to absorb it.

(75.) When the atmosphere holds in suspension any considerable quantity of vapour, as is the case in warm weather, the vapour has a tendency to be condensed on the surface of all bodies exposed to the air, and it collects upon them in a greater or less quantity, according to the attraction which they severally have for it. When a film of moisture is thus collected on the surface of a non-conductor, such a body loses, in effect, its non-conducting power; or, to express more correctly the phenomena, the body becomes enveloped in a thin covering of water, along the surface of which, and not the surface of the body itself, the electricity passes. And water being a conducting body, the deposition of such moisture on the insulating supports of an electrified conductor must give a free passage to the electricity, and therefore destroy the effect of the insulator. In electrical experiments, therefore, besides selecting the best non-conducting substances for insulators, it is necessary to keep them constantly dry by rubbing them occasionally with a dry cloth.

(76.) But even supposing an electrified conductor to be perfectly insulated, a gradual loss of electricity would take place by means of the atmosphere surrounding it. This atmosphere, like all other non-conductors, possesses the insulating power only in an imperfect degree, and this imperfection varies according to the quantity of vapour suspended in it, and probably, also, according to physical modifications produced by variations of heat and other causes which affect the properties of its constituent elements.

In general, the air may be considered as being composed of an infinity of different atoms, which possess the conducting power in different degrees. Each molecule of air which touches the electrified conductor receives a portion of its electricity, and becomes itself electrified. The charge of electricity which it receives depends conjointly on its magnitude and its conducting power, and having an electricity similar to that of the conductor, it is repelled and replaced by another molecule, which is likewise electrified, and in its turn repelled. Thus, by the continued effects of such particles, the electricity of the conductor is progressively diminished.

Since, in practice, the gradual loss of electricity sustained by any electrified conductor is due to the combined effect of the two causes above mentioned, namely, the contact of the surrounding air and the imperfect insulation of the supports, a difficulty is presented in determining how much of the total loss of electricity is due to the one, and how much to the other, of these causes. The means selected by Coulomb to remove that difficulty was the selection of supports composed of the best non-conducting substances, and so reducing their dimensions that the surface which they expose to the humidity of the air is so small that the electricity escaping by the imperfect insulation shall bear so small a proportion to the total loss of electricity sustained, that it may be disregarded, and that the whole loss may, without sensible error, be ascribed to the air.

(77.) After various trials, he found that when the conductor was not very strongly electrified, a rod of sealing-wax or gum lac, about twenty lines in length and half a line in diameter, perfectly insulated a pith ball of five or six lines in diameter. For he found that, whether the ball was supported by a single rod of this kind or by several, the loss of electricity was the same. Now it is evident that the loss produced by the imperfection of the insulating power of these rods would be greater in proportion to the number of them used to support or suspend the ball. If, then, the actual loss when the ball was suspended by six such rods was sensibly the same as when it was suspended by only one, it follows that the loss produced by the imperfect insulating power of a single rod was so small that no sensible difference existed between it and a loss six times greater.

(78.) He found also, that when the atmosphere was dry a thread of fine silk drawn through boiling sealing-wax, so as to have a diameter not exceeding a quarter of a line, was an equally good insulator when its length was not less than six inches. A thread of glass, drawn at the blow-pipe, five or six inches in length, was a sufficiently good insulator when the electricity of the conductor was very feeble, and the air dry. A human hair or a thread of silk, coated with sealing-wax, or a varnish of gum lac, was found to answer the same purpose.

(79.) Having by these preliminary experiments been enabled to select the best insulators, Coulomb attached a pith ball to the extremity of a thread of very pure gum lac twenty lines in length, and the other extremity of this thread he attached to a filament of very fine silk coated with sealing-wax. He considered the ball thus suspended to be perfectly insulated. This ball, so suspended, he introduced at the opening T (*fig.* 4.) in the top of his electrometer, and used it as the fixed ball in his experiments. The moveable ball being, as in the experiment formerly described, attached to a needle of gum lac, and that needle being suspended by a fine silken thread, was also perfectly insulated. In the first instance he submitted to experiment two balls of equal diameter in an electrometer of such sensibility that the torsion produced by one revolution of the needle did not exceed the 340th part of a grain. The two balls being brought into contact were electrified by the head of a pin, as in the former experiments, and the moveable ball was repelled to the distance of 40° from the fixed ball. By turning the thread of suspension the moveable ball was then forced nearer to the fixed ball, and brought to rest, for example, at the distance of 20°. To maintain it at this distance, the angle of torsion was found to be 160°. The moment at which the ball was brought to rest in this position was observed by a watch having a seconds hand, and was found to be fifty minutes after six o'clock.

The apparatus being allowed to remain undisturbed, the gradual loss of electricity by the surrounding air produced a progressive diminution of the repulsive force by which the balls were separated, and, accordingly, the distance of the moveable from the fixed ball was observed to be gradually diminished, and to have become less than 20°. To bring back the moveable ball to its former position, the suspended thread was untwisted by moving the index of the micrometer of torsion through 30°. The moveable ball now, however, was driven beyond its first position, and came to rest at a distance from the fixed ball greater than 20°. The apparatus was again left undisturbed, until, by the further loss of electricity, the distance of the moveable ball was again diminished. The moment at which that distance became 20° was observed, and was found to be fifty-three minutes after six o'clock.

It appears, therefore, that a torsion of 160° was necessary to keep the moveable ball 20° from the fixed ball at fifty minutes after six o'clock; and that a torsion of 30° degrees less was sufficient to maintain it in the same position at fifty-three minutes after six. Thus in three minutes the repulsive force was diminished by an amount corresponding to an angle of torsion of 30°; and as by further experiments it was found that in small intervals of time, the loss is sensibly proportional to the time, it follows that in this case the electricity was lost at the rate of 10° per minute. Now, since the mean repulsive force during the above experiment was 145° (which is a mean between the initial and final repulsive force), it follows that the loss of electricity by the contact of the air was in this case $\frac{10}{145}$, or the twenty-ninth part of the whole mean repulsive force.

By experiments conducted in this manner, Coulomb obtained the results in the following table: —

Time of Experiment.				Distance of Balls.	Torsion of Micrometer.	Time elapsed between two consecutive Observations.	Electrical Force lost between two Observations.	Mean Force between two Observations.	Ratio of electric Force lost per Minute to the mean Force of the Body.
First Experiment, May 28. Saussure's Hygrometer, 75°. Thermometer 60°. Barometer 30·08.									
Exp.	H.	M.	S.			min.			
1	6	32	30	30	150	5¾	20	140	$\frac{1}{40}$
2	6	38	15	id.	130	6¼	id.	120	$\frac{1}{38}$
3	6	44	30	id.	110	8½	id.	100	$\frac{1}{42}$
4	6	53	0	id.	90	10	id.	80	$\frac{1}{40}$
5	7	3	0	id.	70	14	id.	60	$\frac{1}{42}$
6	7	17	0	id.	50				
Second Experiment, May 29. Hygrometer 69°. Thermometer 60°. Barometer 30·16 inches.									
1	5	45	3	30	160	7½	20	150	$\frac{1}{56}$
2	5	53	0	id.	140	9¼	id.	130	$\frac{1}{61}$
3	6	2	30	id.	120	9¾	id.	110	$\frac{1}{54}$
4	6	12	15	id.	100	20¾	30	75	$\frac{1}{58}$
5	6	33	0	id.	70	18	id.	60	$\frac{1}{54}$
6	6	51	0	id.	50				
Third Experiment, June 22. Hygrometer 870°. Thermometer 60½°. Barometer 29,75 inches.									
1	11	53	45	20	100	3	20	90	$\frac{1}{13\frac{1}{4}}$
2	11	56	45	id.	80	3	id.	70	$\frac{1}{11}$
3	11	59	45	id.	60	5¼	id.	50	$\frac{1}{13\frac{1}{2}}$
4	12	5	0	id.	40	11¼	25	28	$\frac{1}{13\frac{1}{2}}$
5	12	16	15	id.	25				
Fourth Experiment, July 2. Hygrometer 80°. Thermometer 60½°. Barometer 30 inches.									
1	7	43	40	20	100	5⅓	20	90	$\frac{1}{14}$
2	7	49	0	id.	80	8⅓	id.	70	$\frac{1}{19}$
3	7	57	20	id.	60	11⅚	id.	50	$\frac{1}{30}$
4	8	9	20	id.	40	8⅓	10	35	$\frac{1}{19}$
5	8	17	30	id.	30				

(80.) From the mere inspection of this table it will be evident, that, on the same day, and in the same state of the air, the loss of the electricity which takes place in equal small intervals of time, bears the same ratio to the whole intensity of the electric force of the body. Thus, in all the six experiments of the 28th of May, the loss per minute was very nearly the same fraction of the total mean repulsive force, the greatest observed amount of loss being $\frac{1}{38}$, and the least $\frac{1}{42}$, part of the whole; and a like correspondence will be observed between the result of all the experiments made on any one day.

But on comparing the rate at which electricity was lost on different days, a striking difference will be observed: thus, on the 22d of June the loss per minute was at the rate of about the 13th part of the whole electric force of the bodies, while on the 29th of May the loss was little more than the 60th part. On comparing the state of the hygrometer on the different days with the results of the experiments, it will be found that in proportion as the hygrometer rose, the loss of electricity increased. On the 22d of June, when the hygrometer was at 87°, a 13th part of the electricity was lost per minute, while on the 29th of May, when the hygrometer stood at 69°, the loss per minute was scarcely a 60th part. It is apparent, therefore, that the loss of electricity increases in some proportion not yet determined, with the quantity of aqueous vapour suspended in the air. It will be observed that, on the four days on which the experiments here recorded were made, the barometer and thermometer had nearly the same altitude.

(81.) If experiments on this subject were extended and varied, they would doubtless lead to the discovery of the exact relation between the quantity of aqueous vapour suspended in the air, and the rate at which electricity is lost. It would also be apparent, whether the loss of electricity is owing exclusively to the aqueous vapour suspended in the air, or in part due to the pressure and temperature of the air itself. The exact solution of these problems would convert the electrometer into the most delicate and precise meteorological instrument, and the determination of the meteorological state of the atmosphere as to its humidity, temperature, and pressure, would probably afford sufficient data to enable us to calculate the rate at which the electricity is dissipated on any given day, independently of experiments.

(82.) In the absence of such data, it is necessary to determine by direct experiment, in the manner above explained, the rate at which electricity is lost by the contact of the air on each particular day on which any experimental enquiry in electricity is made.

A single experiment, however, is in general sufficient for this purpose, since the indications of the hygrometer, thermometer, and barometer do not generally suffer any considerable change in the time occupied by such experiments on any given day, and while they remain the same, the rate at which electricity is dissipated remains unaltered.

(83.) The law which governs the loss of electricity being thus known, it only remains to establish such formulæ as will enable the observer, when the electric state of body, or in other words the intensity of attraction or repulsion at a given distance, is known at any one epoch, to determine what it would be at any other, and thus to enable him to introduce into his calculations those corrections which the loss of electricity by the contact of the air renders necessary. For this purpose let A_0 be the torsion which measures the electric force at the time T_0, and let the successive times be T_1, T_2, T_3, &c. at which, by the gradual waste of electricity, the torsion becomes A_1, A_2, A_3, &c.

In the successive intervals of time expressed by

$$T_1 - T_0,$$
$$T_2 - T_1,$$
$$T_3 - T_2,$$
$$T_4 - T_3,$$

the losses of force expressed by the corresponding elements of torsion will be

$$A_0 - A_1,$$
$$A_1 - A_2,$$
$$A_2 - A_3,$$
$$A_3 - A_4.$$

If we suppose the time expressed as before in minutes, and the torsion in degrees, the first series will express the number of minutes in which are lost the forces equivalent to the degrees of torsion expressed in the second series. Thus, in the number of minutes expressed by $T_1 - T_0$, the loss of electricity is proportional to the number of degrees expressed by $A_0 - A_1$; and as the loss of electricity in one minute will be found by dividing the total loss in any number of minutes by that number, it follows, that the loss of electricity per minute is proportional to

$$\frac{A_0 - A_1}{T_1 - T_0};$$

and as the loss per minute has been proved to be always in the same ratio to the total mean electric force, let this proportion in the present case be expressed by *a*, the mean electric force being half the sum of the initial and final electric forces, and we shall have

$$\frac{A_0 - A_1}{T_1 - T_0} = a \times \tfrac{1}{2}(A_0 + A_1).$$

From which we infer

$$A_1 = A_0 \frac{1 - \frac{1}{2}a(T_1 - T_0)}{1 + \frac{1}{2}a(T_1 - T_0)}.$$

If we suppose the same interval to elapse between each successive pair of observations, and this interval to be expressed by t, we shall have

$$T_1 - T_0 = t,$$
$$T_2 - T_1 = t,$$
$$T \ - T_2 = t,$$
$$T_4 - T_3 = t\,;$$

and by extending the preceding formula to every successive pair of observations, we shall have

$$A_1 = mA_0,\ A_2 = mA_1,\ A_3 = mA_2\,;$$

where, for brevity, $m = \frac{1 - \frac{1}{2}at}{1 + \frac{1}{2}at}$. From these it follows, that

$$A_1 = mA_0,\ A_2 = m^2A_0,\ A_3 = m^3A_0,\ A_4 = m^4A_0.$$

By which, if m and the torsion A_0 at the time T_0 be known, the torsion at any succeeding epoch may be immediately computed. If, in general, n express the order of any observation counted from the first, we shall have $A_n = m^nA_0$.

Since the whole interval from the time T_0 to the time T_n of the n^{th} observation is $T_n - T_0$, and since t is the interval between two succeeding observations, the number of observations n will be found by dividing $T_n - T_0$ by t, and we shall therefore have

$$n = \frac{T_n - T_0}{t}.$$

But we have $A_n = m^nA_0$, $\log. A_n = n \log. m + \log. A_0$. Therefore

$$n = \frac{\log. A_n - \log. A_0}{\log. m}.$$

and therefore we have

$$T_n - T_0 = \frac{t}{\log. m} (\log. A_n - \log. A_0).$$

The relation here expressed between the time $T_n - T_0$, and the quantity of electricity lost, has an apparent dependence on the interval of time t between two successive observations, of which, however, it ought evidently to be independent. It is easy, however, to show that the quantity $\frac{t}{\log. m}$ is really a constant quantity independent of t. Substitute for m its value, and we have

$$\log. m = \log. \frac{1-\frac{1}{2}at}{1+\frac{1}{2}at} = \log. (1-\tfrac{1}{2}at) - \log. (1+\tfrac{1}{2}at).$$

Developing these logarithms in series of powers of t, by the theorem of Taylor, we have

$$\log. (1+\tfrac{1}{2}at) = \frac{1}{M}\left\{\frac{(\frac{1}{2}at)}{1} - \frac{(\frac{1}{2}at)^2}{2} + \frac{(\frac{1}{2}at)^3}{3} - . \right\}$$

$$-\log. (1-\tfrac{1}{2}at) = \frac{1}{M}\left\{\frac{(\frac{1}{2}at)}{1} + \frac{(\frac{1}{2}at)^2}{2} + \frac{(\frac{1}{2}at)^3}{3} + \ldots\right\};$$

in which $M = 2{\cdot}302585$; from whence we infer

$$\frac{t}{\log. m} = \frac{M}{a + \frac{a^3t^2}{3{\cdot}4} + \ldots\ldots\ldots}.$$

But in order that the conclusion at which we have arrived be rigorously true, the interval t must be taken $=0$. Hence

$$\frac{t}{\log. m} = \frac{M}{a},$$

which is independent of t, and dependent only on the rate at which electricity is lost by the contact of the air. Hence we have

$$T_n - T_0 = \frac{M}{a}(\log. A_0 - \log. A_n) \ldots . (1),$$

$$\text{or } \log. A_n = \log. A_0 - \frac{a}{M}(T_n - T_0) . \;.. (2).$$

By the formula (1) we can calculate the interval

$T_n - T_0$, after which the torsion shall have any given value A_n; and by the formula (2) we shall find the torsion, which will be produced by the electrical force after any given interval, $T_n - T_0$.

As an example of the practical application of the preceding formula, let us take the observations of the 28th May, given in the table (79.). In this case the angle of torsion at the moment of the first observation was 150°, and the loss of force was at the rate of $\frac{1}{41}$ of the whole mean force per minute. Let it be required to calculate what the angle of torsion would be after the lapse of 45 minutes. We have then

$$A_0 = 150°, \quad a = \frac{1}{41}, \quad T_n - T_0 = 45.$$

Hence we have

$$\frac{a}{M} = \frac{1}{41 \times 2{\cdot}302585} = 0{\cdot}0105925, \ \frac{at}{M} = 0{\cdot}4766625,$$

$$\log. A_0 = 2{\cdot}1760913.$$

Hence we shall have

$$\log. A_n = 2{\cdot}1760913 - 0{\cdot}4766625 = 1{\cdot}6994288.$$

which gives

$$A_n = 50°\ 3'\ 10''.$$

Now the angle of torsion given by observation was 50°, as appears by the table. The accordance of the calculated and observed angles is perfect, since, in this species of observation, small fractions of a degree cannot be estimated.

(84.) The amount of torsion being thus reduced to computation, it remains to explain the method of deducing from it the actual intensity of the electric force to which this torsion is proportional. If F express the attractive or repulsive force exerted by the electrified bodies at the unit of distance, then $\frac{F}{D^2}$ will express the force exerted at the distance D; and since this bears an invariable ratio to the torsion which measures it, we shall have

$$\frac{F}{D^2}=bA;$$

where A is the angle of torsion corresponding to the force F.

Let F_0 be the force, and A_0 the corresponding angle of torsion at any proposed epoch, and after the lapse of any given interval of time t, let F_t be the force and A_t the angle of torsion; we shall then have

$$\frac{F_0}{D^2}=bA_0, \qquad \frac{F_t}{D^2}=bA.$$

Hence we have

$$\frac{F_0}{F_t}=\frac{A_0}{A_t}, \text{ or } F_t=F_0\frac{A_t}{A_0},$$

which is nothing more than the statement in mathematical symbols, that the electric forces are proportional to angles of torsion. Taking the logarithms we have

$$\log. F_t=\log. F_0+\log. A_t-\log. A_0.$$

But by (2) we have

$$\log. A_t=\log. A_0-\frac{at}{M}.$$

Hence we have

$$\log. F_t=\log. F_0-\frac{at}{M}\ldots.(3).$$

By which the force F_t may be computed when F_0 is known.

The forces which are here submitted to calculation, being the actual attractions or repulsions exerted between two electrified bodies, their total effect is the compound result of the actions of each body on the other; and if these forces separately be expressed by R and R′, we have already shown that F will be equal to their product. Retaining a notation analogous to the preceding one, we shall therefore have

$$F_0=R_0R'_0, \quad F_t=R_tR'_t.$$

(85.) In the experiments of Coulomb, tabulated in (79.), the two electrified bodies were equal balls of the same substance simultaneously and equally electrified. Hence, after the lapse of any time, their electric forces must have been necessarily equal.

Thus we should have $R=R'$, and therefore $F_0=R_0^2$ and $F_t=R_t^2$. Making these substitutions in the equation (3), we shall have

$$\log. R_t=\log. R_0-\frac{at}{2M}.$$

The electric force of each ball, therefore, decreases according to the same law as the angle of torsion. But the co-efficient $\frac{1}{2}a$ of this proportion is only half that of the decrement of torsion. For example, in the experiments of the 28th of May, tabulated in (79.), the decrement per minute of torsion is $\frac{1}{41}$ of the whole mean torsion, while the decrement per minute of the electric force of each ball is only the $\frac{1}{82}$ part of the whole mean electric force of that ball.

It is easy to extend this problem to the case of balls of unequal magnitude. If R R′, be the electric forces of the balls respectively at any moment, the decrement which each suffers per minute will follow the law just explained; so that we shall have

$$\log. R_t=\log. R_0-\frac{at}{2M}, \ \log. R'_t=\log. R'_0-\frac{at}{2M}.$$

From which we deduce by addition

$$\log. R_tR'_t=\log. R_0R'_0-\frac{at}{M} \ldots. (4).$$

Substituting for the products of the separate forces of the balls their values, we have

$$\log. F_t = \log. F_0 - \frac{at}{M} \dots . (5);$$

and therefore

$$\log. A_t = \log. A_0 - \frac{at}{M} \dots . (6),$$

since the forces of attraction or repulsion, compared, as they are here understood to be, at the same distance, are always proportional to the angles of torsion.

It appears therefore, by the result of this investigation, that in the case of unequal balls, the decrement of torsion, by reason of the dissipation of electricity, takes place in the same manner, and according to the same proportion, as in the case of equal balls. The results of the experiments are altogether in accordance with this — whatever be the proportion of the magnitude of the fixed to the moveable ball — whatever be the quantity of electricity first imparted to them, whether they be electrified simultaneously or at different times, equally or unequally — the rate of decrease of the force with which they mutually attract or repel each other, will be invariably proportional to the intensity of that force. It is further to be observed, that the ratio which this rate of decrease bears to the whole amount of the attractive or repulsive force, is the same, whatever be the nature of the electrified bodies. The nature of the matter of which they are formed has therefore no discoverable influence on the rate at which electricity is lost by the contact of the air. This result is in accordance with what has been already stated, that bodies appear to retain the electricity imparted to them not by any peculiar affinity or attraction for it, but only by the mechanical resistance opposed to its escape by the surrounding air. For example, on the day on which the electricity decreased on each of the balls at the rate of $\frac{1}{82}$ part of its whole amount per minute, the same rate of decrease was observed when a ball of copper was substituted for one of the pith balls. A ball of sealing wax charged with electricity by contact with a strongly electrified conductor being substituted for the fixed ball in the electrometer, the same rate of decrease was observed. It appears, therefore, that even in the case of non-conducting bodies, whose surface opposes an obstruction to the transmission of electricity over them, there is no corresponding obstruction to its escape by the contact of the surrounding air; but that, on the other hand, such a body loses its electricity as fast as the most perfect conductor.

The experiments which have been referred to were made on small balls, such as could be conveniently introduced into the electrometer; but the law which has been deduced from them is universal, provided the charge of electricity given to them is not very considerable. Whatever be the figure of the electrified body, whatever be its magnitude, and whatever be the amount of its repulsive force, if only the atmosphere be dry, and the degree of electricity imparted to the body be not considerable, the decrement of the repulsive force per minute will always be the same fractional part of its whole amount, supposing the hygrometric state of the air not to change. Coulomb extended this investigation to bodies of various magnitudes and forms. He submitted to experiment a globe of a foot in diameter with cylinders of various magnitudes and lengths. He substituted for the balls discs of various substances: he tried also the effect of a copper wire ten lines in length and one-fourth of a line in diameter, and found that the decrease of all these different bodies electrified on the same day was the same. It is necessary to observe, however, that this uniform decrease in bodies differing much in figure is only observed when they are charged with a very feeble electricity; for when a strong charge of electricity is given to bodies having an angular form, the rate of its decrease is much more rapid than is the case with round bodies, for reasons which will be explained hereafter. But even these bodies will conform to the law of the uniform decrease of electricity, when their electricity has been so far enfeebled that the angles and points lose their influence.

Biot, to whom the mathematical analysis of the loss of electricity by the contact of the air is due, instituted a series of experiments with a view to determine whether any difference existed at a given time between the rates at which positive and negative electricity were lost. The result of his enquiry was, that these rates were the same.

(86.) It is evident from the results of the numerous and careful experiments instituted by Coulomb, that the quality of the atmosphere which produces the most material effect on the dissipation of electricity, is that which is indicated by the hygrometer; but, notwithstanding the elaborate investigation of that philosopher, he could discover no law of electrical dissipation depending exclusively on the combined indications of the barometer, thermometer, and hygrometer. It appears, therefore, that there is some source of the absorption of electricity independent of variation of the pressure, temperature, and dryness of the air; or, as is perhaps more probable, these instruments are not so immediately affected by atmospheric changes as an electrified body is. Hence it may have happened that on different days, when the barometer, thermometer, and hygrometer indicated the same state of the atmosphere, the quantity of electricity lost per minute would not be the same. On a sudden change of weather, when the hygrometer indicated increased dryness, the quantity of electricity lost per minute was not diminished so much as it ought to have been by calculation. Coulomb accounts for this by the supposition, that there is an adhesion between the air and the vapours which interferes with the indications of the hygrometer, so that the substance, by the qualities of which the indications of this instrument are obtained, can only be affected by that portion of moisture which is entirely disengaged from any combination with the molecules of air; and that, as the separation is effected only by degrees, the dissipation of electricity is promoted by those particles of aqueous vapour remaining in combination with the air, of which the hygrometer is not sensible.

(87.) The same method of experiment which conducted Coulomb to the discovery of the law according to which electricity is dissipated by the contact of the air, would naturally be resorted to ascertain the loss of electricity proceeding from imperfect insulation.

Such a method would consist in the adoption of supports which would produce a loss of electricity bearing a very considerable proportion to the loss sustained by the contact of the air. This would, however, be attended with great practical inconvenience and difficulty. Each time the apparatus is touched, whether it be to electrify the balls or to adjust the torsion of the suspended thread, the needle would continue to oscillate for a considerable time before it would come to rest; and in that interval the intensity of the electricity would suffer great variation; the insulator, therefore, should be at least sufficiently perfect to enable the observer to complete a series of several observations without renewing the electricity of the balls. In the experiments instituted by Coulomb for this purpose, the fixed ball, instead of being suspended by a small rod of gum lac which perfectly insulated it, was suspended by a single fibre of raw silk fifteen inches in length. The moveable ball was, as before, equal to the fixed ball, and perfectly insulated. The apparatus being thus arranged, the experiments were made in the same manner as in the former case, and the decrement of torsion which took place in known intervals of time was observed. As these experiments were made on the 28th and 29th of May, two of the days on which the former experiments were made, the loss of electricity by the atmosphere alone was known, which being deducted from the total loss of electricity, the remainder would be that due to the imperfect insulation of the supports.

The results of the experiments are exhibited in the following table: —

Time of Experiment.				Distance of Balls.	Torsion of Micrometer.	Time elapsed between two consecutive Observations.		Electric Force lost between two consecutive Observations.	Mean Force between two Observations.	Ratio of electric Force lost per Minute to the remaining Force of the Body.
First Experiment, May 28.										
Exp.	H.	M.	S.			M.	S.			
1	10	0	0	30°	180					
						2	30	30	165	$\frac{1}{14}$
2	10	2	30	id.	150					
						5	30	40	130	$\frac{1}{18}$
3	10	8	0	id.	110					
						5	0	20	100	$\frac{1}{23}$
4	10	13	0	id.	90					
						16	30	40	70	$\frac{1}{29}$
5	10	29	30	id.	50					
						21	0	20	40	$\frac{1}{42}$
6	10	50	30	id.	30					
						16	30	10	25	$\frac{1}{41}$
7	11	7	0	id.	20					
Second Experiment, May 29.										
1	7	34	0	30	180					
						2	40	20	170	$\frac{1}{23}$
2	7	36	40	id.	160					
						4	50	id.	150	$\frac{1}{29}$
3	7	41	30	id.	140					
						6	50	id.	130	$\frac{1}{44}$
4	7	48	20	id.	120					
						7	25	id.	110	$\frac{1}{43}$
5	7	55	45	id.	100					
						11	45	id.	90	$\frac{1}{53}$
6	8	27	30	id.	80					
						17	30	id.	70	$\frac{1}{62}$
7	8	25	0	id.	60					
						17	30	15	52	$\frac{1}{58}$
8	8	42	30	id.	45					
						22	30	14	38	$\frac{1}{56}$
9	9	5	0	id.	31					

On inspecting this table it will be evident, that in the commencement, when the repulsive force of the electricity is considerable, the loss of electricity is much more rapid than by the air alone; but, according as the repulsive force is diminished and the electricity becomes more feeble, the rate at which it is lost is diminished, until at last it becomes equal to the rate at which it is lost by the contact of the air alone. Thus, on the 28th of May, in the first experiment, the total loss per minute was a fourteenth of the whole electric force; but when the repulsive force was diminished, so as to be balanced by a torsion of 40°, the quantity lost per minute was equal to that which was lost by the contact of the air alone. When the electricity, therefore, did not exceed this intensity, the insulators became perfect. In the same manner, in the experiments on the 29th of May, the insulation became perfect when the repulsive force was measured by the angle of torsion of 70°.

In these experiments, the moveable ball, being perfectly insulated, loses its electricity only by the contact of the air. The electric force of this ball, therefore, for any time, may be calculated by the formulæ already established for the case of bodies perfectly insulated; and as the experiments supply the value of the whole repulsion of the two balls, that of the fixed ball may be immediately inferred. Let R be the electric force of the moveable, and R'_0 that of the fixed ball at the commencement of the observations, and let R_t and R'_t be their forces after the interval t, and let F_0 and F_t be the total electric force exerted by the balls on each other at the commencement, and at the end of the time t. We have then

$$F_0 = R_0 R'_0, \quad F_t = R_t R'_t.$$

Therefore

$$\frac{F_t}{F_0} = \frac{R_t}{R_0} \cdot \frac{R'_t}{R'_0};$$

$$\log \frac{F_t}{F_0} = \log . \frac{R_t}{R_0} + \log . \frac{R'_t}{R'_0}.$$

But according to what has been already proved with respect to balls perfectly insulated, we have

$$\log.\frac{R_t}{R_0}=-\frac{at}{2M},$$

the number a expressing the decrement per minute, which the electricity suffers by the air alone. The quantity $\frac{F}{F_0}$ is determined by the experiment, being equal to the ratio of the torsions at the commencement and at the end of the time t. Let these torsions, as before, be expressed by A_0 and A_t, and we shall have

$$\log.\frac{R'_t}{R'_0}=\log.\frac{A_t}{A_0}+\frac{at}{2M}\dots.(7).$$

This formula will therefore be sufficient to determine the electrical state of an imperfectly insulated body after the lapse of any given time.

As an example of the practical application of this formula, let it be required to determine the electrical state of the fixed ball at the time when the silk thread of suspension began to insulate it perfectly, in the experiments of the 28th May. Let it be assumed that this perfect insulation commenced after an interval of forty minutes, when the torsion was reduced from 180° to 40°. The decrement of torsion per minute by the operation of the air alone was on that day $\frac{1}{41}$ part of the mean torsion. Hence we have

$$A_0=180,\ A_t=40;\ t=40.\ a=\tfrac{1}{41}.$$

Since $M=2{\cdot}302585$, we shall then have

$$\frac{a}{M}=0{\cdot}0105925,\ \frac{a}{2M}=0{\cdot}0052962,\ \frac{at}{2M}=0{\cdot}2118480.$$

By the tables then we find

$$\log. A_t = 1\cdot6020600,$$
$$\log. A_0 = 2\cdot2552725,$$

$$\log. \frac{A_t}{A_0} = \bar{1}\cdot3467875,$$

$$\frac{at}{2M} = 0\cdot2118480,$$

$$\log. \frac{R'_t}{R'_0} = \bar{1}\cdot5586355,$$

$$\frac{R'_t}{R'_0} = 0\cdot36194.$$

Hence it appears that the thread of silk fifteen inches long became a perfect insulator when the electricity of the ball was reduced to $\frac{36}{100}$ of its original amount.

The original electric force of the fixed ball may be easily determined. We have $F_0 = R_0 R'_0$. But since the balls are equal, and similarly and simultaneously electrified, $R_0 = R'_0$. Therefore

$$F_0 = R'^2_0, \text{ and } R'_0 = \sqrt{F_0}.$$

But if $\frac{F}{D^2} = bA_0$ we shall have

$$R'_0 = D\sqrt{bA_0},$$

$$R'_t = 0\cdot36194 D\sqrt{bA_0}.$$

But since $A_0 = 180$, we obtain by taking the square root

$$R' = 4\cdot85592 D\sqrt{b}.$$

The state of the air remaining the same, Coulomb repeated this experiment with a thread of the same silk five feet long, being four times the length of the former, and he found $R' = 9\cdot71184 D\sqrt{b}$. As the experiment was made with the same apparatus, and the distance D was the same in both cases, it is evident, that by increasing the length of the insulating thread in the ratio of four to one, its insulating power was increased in the ratio of two to one.

(88.) This principle may be considered as applicable to all cylindrical supports of very small diameter, whose insulating power is imperfect. In a given state of the atmosphere, the intensity of the electric force at which they begin to insulate perfectly is proportional to the square root of their length, their nature and diameter being the same. When the insulating powers of different substances are required, the ratio must be deduced by means of the formula itself from direct experiment. By calculating thus, the electric forces at which threads of gum lac and silk of equal length and the same diameter begin to insulate perfectly, Coulomb found that its value was ten times greater for gum lac than for silk. In the same manner, the insulating power of all substances may be compared and reduced to numerical estimation.

In such experiments it is not necessary that the balls of the electrometer should be observed at the same distance in the two series of experiments: it will be sufficient that this distance be maintained constant in each series, and that its value be substituted in each case in the formula.

It is also indifferent what degree of electricity is imparted to the balls, provided only equal balls similarly suspended, and simultaneously electrified, be used in all those parts. If this condition were not fulfilled, the co-efficient B would not be the same in the different series, which would render their comparison difficult and indirect.

CHAP. V.

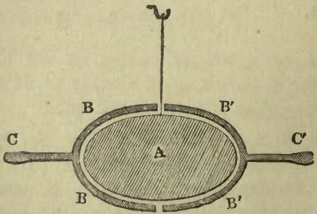
DISTRIBUTION OF ELECTRICITY ON CONDUCTORS.

(89.) By what has been explained, it is apparent that when electricity is communicated to any point of an insulated conductor, it is immediately diffused over its entire surface; but whether on every part of that surface its distribution is the same, or if not, according to what law its energy at different parts of the surface varies, and whether it penetrates beyond the surface to the internal parts of the body, are questions which still remain to be investigated.

Several of the facts which have been already explained render it highly probable, that the electricity which is imparted to conductors is confined to their surface, and that none of their particles, sensibly below the surface, are affected by, or produce any effect upon, it. A ball formed of any material will be equally electrified, whether it be solid or hollow; and if it be hollow, the charge which it receives from any source of electricity will be the same, whether the shell of matter of which it is formed be thin or thick.

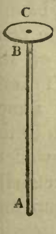
To reduce this question to direct experiment, let A (*fig.* 11.) be a conductor of an oval or spheroidal form;

Fig. 11.



let two thin hollow covers B B′ be formed to correspond with the shape and magnitude of the conductor A, so that, when applied to it, they shall form a coating, which shall completely cover it, and be in close contact with it. Such cover may be formed of paper, gilt on the concave side. Let C C′ be two handles of gum lac attached to these covers, by which they may be applied to the body A, and removed from it without either imparting electricity to them, or allowing any to escape from them. Let the body A be now placed on an insulating support, or suspended by a thread of fine silk, varnished with gum lac, and let it be electrified in the usual way. After having touched the two inner covers B B′ to deprive them of any electricity they may have, let them be applied to the conductor A, holding them by the insulating handles C C′. After withdrawing them from A, they will be found, if tested by the electrometer, to be electrified with the same electricity as was previously communicated to A; and if A be similarly tested, it will be found to have lost all its electricity. Thus, by mere superficial contact, all the electricity which had been previously imparted to A has been taken away upon the covers B B′. To this experiment it may, however, be objected, that the attraction of the surface of the covers B B′ may have been sufficient to draw the electricity from a depth more or less considerable within the surface of the conductor A.

Fig. 12.



(90.) The following experiment made by Coulomb indicates in a manner still more direct the superficial distribution of electricity; and the result is more general, being applicable to bodies of any form whatever. Several small round holes, of less than half an inch in diameter, and of various depths, are made in different parts of the surface of a conductor. A thread of pure gumlac A B (*fig.* 12.), several inches in length, is then attached to a small disc C of gilt paper, the diameter of which is about a third of the diameter of the holes.

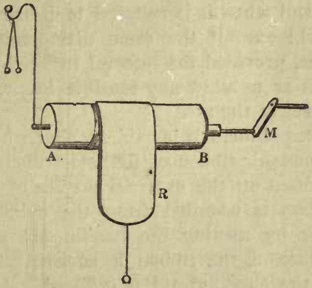
The conductor being insulated, is then strongly electrified by sparks taken from the prime conductor of an electrical machine. Holding the insulating handle of gum lac at A, the disc C is then introduced into one of the holes so carefully as not to touch their edges, and being brought into contact with the surface of the conductor at the bottom of the hole, it is withdrawn with the same precaution. This disc C being then tested by an electrometer, will be found to have acquired no electricity whatever; and the same result will be obtained by introducing it in the same manner into each of the holes. The successful result of this experiment may be rendered more certain by providing a tube of glass, corresponding in magnitude with the holes, which being introduced into them before the disc, the latter may be inserted in the tube, so as to be defended from contact with the edges of the hole.

If the disc C be applied to any part of the surface of the conductor not perforated, or even to the very edges of the holes, it will be found, on withdrawing it from the surface, to be strongly electrified.

From this experiment it appears, that the distribution of electricity upon bodies is confined to their surfaces; but an effect is sometimes observed, which might lead to the supposition that the surface at the bottom of the hole is electrified with electricity of a contrary kind to that of the surface of the conductor; for if the conductor be positively electrified, the disc, after being withdrawn from the hole, is sometimes found to have a feeble charge of negative electricity; and, if the conductor be negatively electrified, the electricity of the disc is found in similar cases to be positive. This is observed to take place more especially when the atmosphere is humid, the gum lac not pure, and when in the performance of the experiment the disc is allowed to remain a considerable time in the hole. The electricity of the disc in such cases does not proceed from any electricity taken up from the surface of the bottom of the hole, but is an effect produced by the electricity diffused on the surface of the conductor acting in a peculiar manner, which will be explained hereafter, on the natural electricity of the gum lac.

(91.) The superficial distribution of electricity on conductors, may be also illustrated by the following experiment:—Let A B (*fig.* 13.) be a cylinder of metal,

Fig. 13.



insulated, and capable of being turned on a horizontal axis by a handle M formed of glass, so that, when held by the hand, no electricity shall pass from the conductor to the hand. Let R be a piece of metallic leaf or foil sufficiently strong to be raised without being broken, and let this be rolled several times round the cylinder, and terminated in a semi-circle, which shall hang from the side of the cylinder. To the lowest point of this semi-circle let a thread of silk F be attached. To the end of the conductor let an electrometer be fixed, consisting of two pith balls, suspended by metallic wires or threads of linen, or other conducting substance. Let the conductor be now electrified. The electricity having free passage to the pith balls, they will repel each other, and the extent of their divergence will be proportional to the intensity of the electricity of the conductor. If the metallic covering R be now unrolled from the cylinder by taking hold of the silk thread F, the divergence of the balls will gradually diminish; and, when the covering is entirely unrolled, the balls will exhibit no sensible divergence. The silk thread by which the metallic covering is sustained being an insulator, the electricity will be retained on the surface of the metal, and will not escape to the hand. If the metallic covering be now again rolled upon the cylinder, the balls will gradually diverge, their divergence increasing as the covering is successively rolled up; and when it is restored to its first position, the balls will exhibit the same divergence as in the first instance, provided the interval suffered to elapse be not so great as to allow any sensible loss of electricity by the contact of the air.

In this experiment it is evident, that when the conductor and metallic ribbon are first electrified, the electric fluid is diffused on the external surface of the ribbon. As the ribbon is unrolled from the cylinder by the thread F or by turning the handle M, a more extensive surface of the ribbon is successively exposed, over which the electric fluid is diffused. Its intensity diminishes as this surface increases; and if the ribbon be sufficiently long, the surface over which it is distributed will become so extensive, and its intensity will be consequently so diminished, that it will cease to produce any sensible effect upon the balls. When the ribbon, however, is again rolled upon the cylinder by turning the handle M in the other direction, the electricity will again be collected on the same surface on which it was originally diffused, and it will recover its original intensity, and the balls will again diverge.

(92.) Although these experiments satisfactorily prove that the distribution of the electric fluid is either rigorously confined to the surface of bodies or very nearly so, there are some circumstances which render it probable that it penetrates to some depth below their surface, but to so small a depth as to be inappreciable by any known methods of measurement. At so early a period of electrical investigation as the middle of the last century, it occurred to Watson, and about the same time to Lemounier, to try whether the electric fluid passed within the external surface of a metallic rod; and for this purpose the rod was coated through a portion of its length with sealing wax, which, being a non-conductor, would not allow the electric fluid to pass either along its outer surface or along its inner surface, which was in contact with the surface of the metal. A charge of electricity, however, even of feeble intensity, communicated to one end of the rod, passed as freely through its entire length as if there was no coating of wax upon it. It follows from this experiment, that the electricity must have passed sufficiently below the external surface of the metal to be out of contact with the wax.

(93.) Having thus proved the distribution of electricity to be nearly superficial, it now remains to examine whether its intensity on every part of the electrified surface of a conductor is the same. There are some bodies whose geometrical properties suggest so strongly the necessity of uniform distribution as to render demonstration unnecessary. If the electrified body, for example, be a sphere of metal or any other conducting substance, the symmetry of its figure alone renders the uniform distribution of electricity upon it inevitable, since no reason can be assigned why the electricity should be stronger in any one part of the sphere than in any other. If, then, electricity be regarded as a material fluid diffused over the surface of the sphere, having a uniform but extremely small depth on every part of it, as a liquid might be diffused over the surface of the globe, then the total quantity of electricity upon the sphere will be found by multiplying the surface of the sphere by the depth of the fluid. It is proved in geometry that the surface of a sphere is four times the magnitude of the area of one of its great circles, that is, of a section of the sphere made by cutting it through its centre. If, therefore, four times the area of such a circle be multiplied by the supposed depth of the electricity, the total quantity of electricity will be obtained.

Let R be the radius of the sphere, and $\pi = 3\cdot1415$, then the area of the great circle of the sphere will be $R^2\pi$; and if x express the thickness or depth of the electric fluid, the quantity of electricity upon the sphere will be expressed by $4xR^2\pi$; so that, if E be the quantity of electricity, we shall have

$$E = 4xR^2\pi.$$

And if E' be the quantity of electricity on another sphere whose radius is R', and on which the thickness of the fluid is x', we shall have

$$E' = 4x'R'^2\pi.$$

Hence it follows, that the electricities of two spheres will be proportional to the squares of their radii multiplied by the depths of the electric fluid upon them, which is expressed mathematically by

$$\frac{E}{E'} = \frac{xR^2}{x'R'^2}.$$

It follows also that the quantities of electricity on spheres similarly electrified, will be in the proportion of the squares of their radii or diameters, for in that case $x = x'$

(94.) It has been here assumed, that, by imparting an increased charge of electricity to a sphere, the thickness of the shell of electric fluid by which it is enveloped is proportionally increased, which involves the supposition that the density of the electric fluid remains the same. If it be supposed, on the other hand, that each addition made to the electricity leaves the depth of the fluid the same, it must be assumed that its density is increased in the same proportion as the quantity of electricity imparted to it is augmented. On such a supposition the symbol x in the above formula would express the density of the electric fluid and not its depth; and, subject to this modification, the preceding reasoning and the formula will still hold good. It is, in a word, indifferent whether the increased energy or intensity of the electricity be ascribed to the increased depth or increased density of the fluid; for the depth of the fluid, whether variable or not, always bearing an infinitely small proportion to the magnitude of the surface on which the electricity is diffused, the attraction or repulsion it exercises is the same as if all its particles, superposed on one another, were condensed into a single point.

(95.) The electrometer of Coulomb supplies the means of determining by immediate experiment the distribution of electricity on the surfaces of electrified conductors. For this purpose, the disc of gilt paper attached to the handle of gum lac already described is used. This disc is applied to any part of the surface of an electrified conductor, where the intensity of the electricity is to be ascertained. It is then introduced into the electrometer of torsion, and placed opposite the ball or a similar disc electrified with the same kind of electricity attached to the extremity of the needle. The intensity of the electricity with which it is charged is estimated by the torsion necessary to bring the moveable ball or disc of the electrometer within a given distance of it. Let us suppose, for example, that after applying the disc C (*fig.* 12.) (which we shall call the *proof plane*) to any point of an electrified conductor, it is introduced into the electrometer, and is observed to repel the moveable disc similarly electrified. Let the micrometer of torsion be now turned until the moveable disc is brought within 20° of the proof plane, and let the angle of torsion necessary to keep it there be 80°. Let the proof plane be now removed from the electrometer and applied to another part of the conductor, and let it be again introduced into the electrometer. Let the micrometer of torsion be adjusted, so that the moveable disc shall be maintained at a distance from the fixed disc less than 20° by the angle of torsion, which would be lost by the contact of the air in the interval between the two experiments; and let the torsion necessary to maintain it in this position be again observed, and suppose its amount to be 120°. It will follow then that the intensities of the electricity at the two points of the conductor to which the proof disc has been applied, or, what is the same, the depths or densities of the electric fluid at those points will be in the ratio of 80 to 120, or of 2 to 3. If therefore it can be assumed, that the electricity of the proof plane after touching the conductor is really proportional to the electricity of the conductor at the point of contact, the manner in which electricity is distributed over the surface of different conductors may always be determined by thus applying the proof plane to various points upon them, and determining the force of its electricity in the electrometer.

(96.) The first important conclusion to which such an experimental inquiry has led is, that on a conductor of any given form and magnitude the distribution of electricity is always the same, whatever be the depth or density of the electric fluid with which the conductor is charged. This is easily rendered manifest. An insulated conductor being strongly electrified, let the proof plane be successively applied at several points, P, P′, P″, P‴, &c. &c. and let it be successively tried in the electrometer after each contact. Let the torsions representing the repulsive force it exerts at a given distance after each contact be T, T′, T″, T‴, &c., the loss of electricity by the contact of the air upon the moveable disc of the electrometer being duly allowed for. Let the conductor be now discharged by touching it, or otherwise putting it in communication with the earth, and let it be again electrified with a greater or less force than before. Let the proof plane be again brought into contact with the same points P, P′, P″, P‴, &c. &c. as before, and let it, as before, be tested in the electrometer. Let the torsion corresponding to those points be now t, t', t'', t''', &c. These several angles of torsion will express, as before, the electric force which the proof plane has acquired by contact with the conductor at the several points.

Now, if the quantities T, T′, T″, T‴, &c. be compared severally with the quantities t, t', t'', t''', &c., they will be found to be exactly proportional, each to each, so that the following mathematical condition will be fulfilled: —

$$\frac{T}{t}=\frac{T'}{t'}=\frac{T''}{t''}=\frac{T'''}{t'''},\ \&c.\ \&c.$$

Thus, if it were observed that in the second electrical state produced upon the conductor the torsion t were only one-third of the torsion T, it would follow that the depth or density of the electricity at the point P was three times greater in the first case than in the second; and it would accordingly be found that the torsions T′, T″, T‴, &c., expressing the depths of the electricity at the points P, P′, P″, P‴, &c., would be three times the torsion t', t'', t''', &c., expressing the depths of electricity at the same points in the second case; and, in general, that the depth of the electricity on every part of the conductor in the first case would be three times its depth on the same parts of it in the second.

(97.) It follows, therefore, that the total quantity of electricity with which any given conductor is charged at different times is always proportional to the quantities of electricity found by the proof plane at these times on any given point of it.

(98.) If an electrified conductor be tried at a given point by the proof plane after equal successive intervals of time, it will be found that its electricity is subject to a gradual diminution; and if this diminution per minute be calculated, it will be found to be precisely the same as would be produced by the contact of the air, provided the conductor is well insulated, which is therefore evidently the cause of the gradual diminution of its electric force. This may be verified in the following manner: — Let a proof plane be applied to any point of the conductor, and introduced into the electrometer; after remaining there any given time, for example five minutes, it will be observed that the moveable disc will gradually approach it, by reason of the loss of electrical force by the contact of air. Let the moveable disc be restored to its proper distance by diminishing the torsion which retains it. Let another similar proof disc be now applied to the same points of the conductor, and let it be introduced into the electrometer in place of the former. It will be found that the moveable disc will be held in the same position by its repulsion, without any change in the torsion. It follows, therefore, that the loss of electricity sustained in any given time by any part of the surface of the conductor is exactly the same as the loss which would be sustained in the same time by the proof disc electrified by contact with the conductor. In other words, the conductor itself, and the discs electrified at any point of it, undergo the same changes of electrical force in the same intervals of time.

(99.) If it be desired to obtain the exact ratio of the electric densities at any other point of an electrified conductor, independently of any computation of the loss of electricity by the contact of the air, it may be done in the following manner:—Let the proposed points be P and P′, and let the proof plane be first applied to the point P, and its repulsive force be determined by the electrometer. Let it then be applied to the point P′, observing the interval between the two contacts by a watch having a seconds hand, and let its repulsive force be again observed. After the lapse of an equal interval of time, let it be again applied to the point P, and let the electric force be again observed in the electrometer. If half the sum of the two angles of torsion obtained after the two contacts with the point P be taken, it will be the angle of torsion which would have been obtained if the two points P and P′ had been touched by the proof plane at the same moment. The ratio of the torsions, and therefore of the electric densities, at the points P and P′, will thus be obtained independently of any computation of the loss by atmospheric contact, or of any other supposition, save that the loss of electricity in the interval between the first contact with the point P and the contact with the point P′ was equal to the loss in the equal interval between the contact with the point P′ and the second contact with the point P.

(100.) The following experiment will further corroborate the proposition, that the quantities of electricity taken by the proof plane from the same point of a conductor at different times are proportional to the whole quantities of electricity with which the conductor is charged at those times. Let two equal cylinders of metal or of metallic surface, whose lengths are much greater than their diameters, be placed on insulating supports, and let one of the two be strongly electrified. Let the proof plane be applied to it first at a point near the middle of its length, and next at a point near its extremity, it will be found by the electrometer, that the electrical forces at these two points are very different. Let them, however, be exactly observed. Let the second insulated cylinder, which was not electrified, be now placed beside the other, so that their extremities shall exactly coincide, and let them thus be brought into lateral contact. From the perfect regularity and symmetry of the two cylinders and from their conducting power it follows, that the electricity with which the one was previously charged will now be diffused uniformly over the surfaces of both, and that the first will be only charged with half its original quantity. Let them be separated, and let the first be touched at the same points as before by the proof plane, and it will be found, by the indications of the electrometer, that the electrical force of the proof plane will in each case be exactly ahalf what it ws before. This result may be further verified by touching the other cylinder at corresponding points, when the electric forces manifested by the proof plane will be the same.

(101.) To determine by means of the proof plane and the electrometer the actual quantity of electricity with which a conductor at any point is charged, it will be necessary to determine the ratio of the electricity with which the proof plane becomes charged in touching a conductor to the electricity with which the portion of the surface of the conductor so touched was charged. With a view to the solution of this question, Coulomb made the following experiment: he placed a globe eight inches in diameter upon insulating supports, and charged it, as well as the moveable disc of the electrometer, with positive electricity. To determine the electric force of this globe, he brought into contact with it another of an inch in diameter insulated by a handle of gumlac. This latter being introduced into the electrometer, it was found that an angle of torsion 144° was necessary to hold the moveable disc at a given distance from it. He next brought an insulated circular disc of metal, sixteen inches in diameter, in contact with it; after removing which, he again brought the small globe into contact as before with the great one, and again introduced it into the electrometer, when he found that an angle of torsion of 47° was sufficient to keep the moveable disc at the same distance from it.

The insulated disc, sixteen inches in diameter, had a surface on each of its faces equal to four times the area of a circle eight inches in diameter, and therefore a total surface equal to eight times the area of such a circle; but the surface of a globe eight inches in diameter is proved in geometry to be equal to four times the area of a circle of the same diameter. It consequently follows, that the surface of each face of the great disc is equal to the whole surface of the greater globe; and therefore, that the total surface of both faces is double the surface of the globe. When this disc is therefore brought into contact with the globe, the electricity which was previously diffused upon the globe is diffused over the united surfaces of the globe and the disc; that is, over three times the surface to which it was before confined. If it be diffused uniformly on these surfaces, it will be therefore three times less dense on the greater globe after the contact of the disc, than it was before. In the second experiment made with the inch ball, the repulsive force was found to correspond to an angle of torsion of 47°, which would be a third part of 141°, which is little different from the actual angle of torsion 144° obtained by the first experiment. Since the repulsive force of the smaller globe in the two cases is proportional to the depth of electricity on the greater globe, it follows that this depth is in the ratio of three to one; and therefore, that by the contact, the disc has taken from the globe two-thirds of its charge of electricity, and consequently that the depth of electricity on the plane after contact is the same as the depth of electricity remaining on the globe.

Had the disc been electrified and the globe not so, the result would have been the same. In that case, the globe would have received one-third of the charge of electricity upon the disc. Coulomb verified this by a great variety of experiments, and found in general, that whatever the magnitude of the disc might be, the quantity of electricity it required always bore to the quantity remaining on the globe the ratio which the area of the two sides of the disc bore to the area of the surface of the globe. It follows, therefore, that when the disc becomes so small that its total surface bears a very minute proportion to that of the globe, the quantity of electricity it takes from the globe bears no sensible proportion to the quantity remaining on the globe; the disc, therefore, carries away upon each of its faces as much electricity as covers the portion of the globe with which it is brought into contact, and consequently the total quantity of electricity taken upon the disc at each contact must be double the quantity which covers an equal part of the surface of the globe. The angle of torsion, therefore, produced by the repulsive power of this electricity, will be double that which would be produced by the electricity diffused upon a portion of the globe equal in magnitude to the area of the disc.

(102.) By the frequent repetition of such experiments, the electricity taken from the globe by the proof plane would diminish in a slight degree the absolute quantity of electricity; and consequently, to be enabled to compare together the results of a succession of observations so made, it would, in strictness, be necessary to take into account this gradual diminution of the electric force. This precaution is, however, rendered needless if the magnitude of the proof disc bears so small a proportion to the magnitude of the surface of the conductor, that the whole quantity of electricity which it takes away in any one series of experiments bears an insignificant proportion to the quantity which remains on the conductor; but if this precaution be considered insufficient, it is only necessary to bring back the proof disc to the conductor in each experiment without discharging it. By such means the only diminution of electricity which will take place will be that due to the contact of the air, which can be computed and allowed for as already explained.

(103.) In the practical application in this method of experimenting the results of the experiments are sometimes exposed to a source of error against which it is necessary to provide. The rods of gum lac used to support the proof discs are imperfect non-conductors, and are capable of absorbing, in a sensible degree, the electricity of the disc. The errors arising from this source are greater in proportion to the humidity of the air; but they are also dependent on the nature of the gum lac itself, which possesses the insulating power in different degrees, according to its purity. That which has the darkest colour is generally the best, but the colour alone can hardly be depended on as a test of purity. The gum lac must be tested by experiment, before it is employed in investigations requiring such extreme delicacy. With this view, when the threads are formed of the requisite thickness and length, it is necessary to bring the extremity intended to bear the proof disc in contact with a strongly electrified conductor, after which it should be presented to the moveable disc of an electrometer charged with electricity of the same kind. If it produces a sensible repulsion, it must be rejected, and such threads only retained as produce no repulsion. For if threads be used which are not almost perfect insulators, the succession of contacts which are made by the disc with the electrified conductor would at length impregnate a portion of the handle of the gum lac by which they are supported with the electricity of the conductor, and when once the gum lac should thus absorb any portion of electricity, it would be extremely difficult to remove it, and a permanent source of error would be produced, which would augment the electric force of the proof disc after each contact.

This effect would be greater for feeble electricities, and would entirely vitiate and render useless all experiments made on parts of the conductor weakly electrified. Considering this source of error, there is an advantage in the employment, in such experiments, of conductors of some considerable magnitude, for, in that case, a proportional magnitude may be given to the proof plane, and the proportion will be lessened in which its electricity will be affected by the electricity, if any, which may be absorbed by the handle of the gum lac.

(104.) The following practical example of the application of this species of experimental investigation has been extracted by Biot, from the unpublished manuscripts of Coulomb.

He proposed to determine how the electricity was distributed upon a thin insulated plate of metal. For this purpose he insulated a plate of steel eleven inches in length, one inch in width, and half a line in thickness. To be able to touch it in its whole width, he made the proof plane an inch long and three lines wide. He first applied this plane at the centre C of the plate A B (*fig.* 14.), and then at P and Q points, one inch from its extremities, and he obtained the following results: —

	Torsions observed.	Mean torsion at centre.	Mean torsion at 1 inch from extremity.	Ratio of the mean torsions.
At centre -	370°			
At 1 inch from extremity -	440	360	440	1·22
At centre -	350	350	417·5	1·20
At 1 inch from extremity -	395	335	395	1·18
At centre -	320			
			Mean - -	1·20

(105.) Thus, on equal spaces taken across the whole width of the plate, at the centre, and at points one inch from its extremities, the quantities of electricity are as 10 to 12, and, consequently, nearly equal, the excess being in favour of the electricity towards the extremities. Coulomb repeated these experiments, but instead of applying the proof plane at points an inch from the extremities, he applied it close to the extremities, so as to obtain the quantity of electricity covering a portion of the plate extending three lines from the end. The results of these experiments are given in the following table: —

	Torsions observed.	Mean torsion at centre.	Mean torsions at extremity.	Ratio of mean torsions.
At extremity -	400			
At centre -	195	195	395	2·02
At extremity -	390	190	390	2·05
At centre -	185	185	370	2·00
At extremity	350			
			Mean - -	2·02

It will be observed that, in this case, the excess of electricity at the ends, compared with the centre, is much greater than in the former case. In fact, while the quantity of electricity upon the plate is nearly uniform from the centre to within an inch of the borders, it is augmented rapidly towards the edges, where it becomes more than double its amount at the centre.

(106.) Coulomb extended this inquiry still further, by applying the proof plane, not on the surface of the plate itself, but in the space corresponding to the prolongation of the plate beyond its extremities A and B, in such a manner that the edge of the proof plane coincided with the extreme edges of the ends of the plate, the proof plane, however, lying beyond the limits of the surface of the plate. The results of these experiments are given in the following table:—

	Observed torsions.	Mean torsions at centre.	Mean bodies beyond the edge.	Ratio of mean torsions.
Centre - -	305°			
Beyond edge -	1175	295	1175	3·98
Centre - -	285	285	1156	4·05
Beyond edge -	1137			
		Mean	- -	4·01

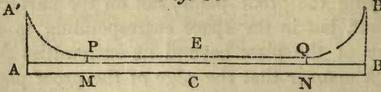
It appears thus that the proof plane, beyond the limits of the plate, acquired an electricity four times that which it acquired at the centre, and double that which it acquired at the extremities.

The experiment being repeated with a plate twenty-two inches long, or double the former length, and of the same dimensions in other respects, exactly the same results were obtained.

(107.) Coulomb concluded, *first*, that the proof plane in these experiments only acquired the electricity of that side of the plate to which it was applied; and, *secondly*, that no increase of length of the plate beyond a certain limit of length, sufficient to enable the electricity to become uniform on the middle portion of its surface, produced any sensible effect on the ratio of the quantity of electricity at the extremity, and at the middle. The first being always double the second.

(108.) To render the result of these experiments more apparent, let A B (*fig.* 14.) represent a plate

Fig. 14.



whose length surpasses the limit necessary to insure a uniform depth of electricity at the centre C. Let perpendiculars, such as P and Q, be drawn to represent the depths of the electricities at the different points of the plate, and let the curve formed by the ends of such perpendiculars be A′ P E Q B′, the curve between the points P and Q will hold its course parallel to the surface of plate A B, all its points being equally distant from the surface of the plate; but from P to A′, and from Q to B′, the curve rises by the increased length of the perpendiculars until A A′ and B B′ are double the magnitude of the perpendiculars between P and Q. Now, since the ratio of these extreme particulars to the centre perpendicular C E is the same in all plates whose length is considerable compared with their width, and since the intermediate ordinates between P and Q are the same in all, it follows that the curves A′ P and B′ Q have the same magnitude in all plates, whatever be their length; and that they consequently designate the varying thickness or density of the electricity at the extremities of all such plates. We are thus enabled to predict perfectly the electric state of any part of such plates when the electricity of the centre has once been observed.

(109.) This rapid increase of electricity towards the extremities of long and narrow plates of metal is not peculiar to them. An analogous effect is observed in all bodies of a prismatic or cylindrical form, whose lengths are considerable in proportion to their thickness, and the increase of electricity at their extremities is found to be so much the more rapid as they are thinner. Coulomb insulated a circular cylinder, two inches in diameter and thirty inches in length, of which the ends were hemispherical, and on comparing, as in the former case, the quantities of electricity collected at the centre, and at points near the extremities, he obtained the following results. At two inches from the extremity the electricity was to that at the centre as $1\frac{1}{4}$ to 1; at one inch from the extremity it was as $1\frac{4}{5}$ to 1; and at the extremity it was as $2\frac{3}{10}$ to 1.

(110.) The manuscripts of Coulomb supplied analogous experiments to determine the distribution of electricity upon thin circular plates, which have likewise been published by Biot. He touched these plates at different distances from their centre with the proof plane, and ascertained by the electrometer, as in the former experiments, the quantity of electricity at different places upon them. In the following table, the result of experiments made in this way upon a plate of copper ten inches in diameter are given.

Distances from the edge.	Depths of electricity.
5 centre of the disc.	1
4	1·001
3	1·005
2	1·17
1	1·52
0·5	2·07
0	2·90

(111.) To express, in mathematical language, the relation between the quantities of electricity, and the distances from the edge of the plate, let y express the intensities of the electric forces, the unit being the force at the centre, and let x express the distances from the edge of the disc in the first column of the above table.

M. Biot proposes the following formulæ obtained empirically to express this relation:

$$y = 1 + A\,(m^{x} - m^{2r-x})$$

In which r is the radius of the disc, and A and m constants, whose value are to be determined by observation. To obtain the value of A, let $x = O$, and for y substitute 2·90, which is the value of y at the edge of the disc, and we have

$$2{\cdot}90 = 1 + A\,(1 - m^{2r}).$$

But since $r = 5$, this becomes

$$2{\cdot}90 = 1 + A\,(1 - m^{10}).$$

It will appear presently that m is a fraction, not exceeding three-tenths, and consequently that its tenth power may be neglected; hence we have by the above equation,

$$A = 1{\cdot}9.$$

To determine the value of m let $x = 1$, and the corresponding value of y being 1·52, we shall find $m = 0{\cdot}27$. But, on comparing the other observations, it will be found that 0·3 is a value of m more in accordance with them. The value m being thus determined, the values of x and y may be found by calculation, and compared with those obtained with experiment. In the following table, the observed and calculated values of y are given, and their near accordance sufficiently proves, that the empirical formula of M. Biot represents with great accuracy the phenomena.

Distances from the centre.	Depths of electricity.		Difference.
	By formula.	By observation.	
5	1·000	1·000	0·000
4	1·014	1·001	+0·013
3	1·051	1·005	+0·046
2	1·170	1·170	0·000
1	1·570	1·520	+0·050
0·5	2·041	2·070	−0·029
0	2·900	2·900	0·000

(112.) It appears in general, from the experiments of Coulomb, that the depth of the electric fluid on a conductor always increases in a rapid proportion in approaching the edges, and that this increase commences at a certain small distance from those edges; thus, when a circular disc or rectangular plate has any considerable magnitude, the density of the electricity is uniform throughout those parts of its area not contiguous with its borders, and whatever be the figure of the conductor, whether round or square, if only it be terminated by sharp angular edges, the density of the electricity will be found to increase at all parts contiguous to those edges.

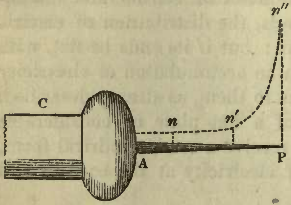
(113.) If a conductor be terminated not by sharp angular edges, but rounded sides or ends, then the distribution of electricity will again become more uniform. Thus, if a cylindrical conductor of considerable diameter have hemispherical ends, the distribution of electricity on it will be uniform: but if its ends be flat, with sharp circular edges, then an accumulation of electricity will take place contiguous to them, as already described. If the sides and ends of a flat plate of considerable thickness be rounded or receive a semicylindrical form, then the accumulation of electricity at the borders will cease.

(114.) The increase of electrical density at the angular edge of a conductor produces still more augmented effects at its corners, where the increase of density due to two edges are in fact combined, and this effect is still further increased if any part of a conductor have the form of a *point*.

(115.) It has been shown that the pressure of the surrounding air is the principal, if not the only, force which retains the electric fluid upon a conductor. Now it is evident, that if at the edges, corners, or angular points of a conductor, the electric depth be so much increased that the elastic force of the electric fluid shall exceed the restraining pressure of the atmosphere, the electricity must escape. Let P (*fig.* 25.) be a metallic point attached to a conductor C, and let the perpendicular *n* express the thickness or density of the electric fluid at that place, this thickness will increase in approaching the point P, so as to be represented by perpendiculars drawn from the respective points of the curve $n\ n'\ n''$ to A P, so that its density at P will be expressed by the perpendicular n'' P. Experience shows, that, in ordinary states of the atmosphere, a very moderate charge of electricity given to the conductor C will produce such a density of the electric fluid at the point P, as to overcome the pressure of the atmosphere, and to cause the spontaneous discharge of the electricity. The following experiments will serve to illustrate this escape of electricity from points.

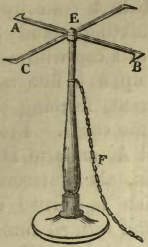
(116.) Let a metallic point, such as AP (*fig.* 15.), be attached to a conductor, and let a metallic ball of two or three inches in diameter, having a hole in it corresponding to the point P, be struck upon the point. If the conductor be now electrified, the electricity will be diffused over it, and over the ball which has been struck upon the point P. The electric state of the conductor may be shown by a quadrant electrometer being attached to it. Let the ball now be drawn off the point P by a silk thread attached to it for the purpose, and let it be held suspended by that thread. The electricity of the conductor C will now escape by the point P, as will be indicated by the electrometer, but the ball suspended by the silk thread will be electrified as before.

Fig. 15.



(117.) Let two wires AB and C D (*fig.* 16.), placed at right angles, be supported by a cap E upon a fine point at the top of an insulating stand, and let them communicate by chain F with a conductor kept con-

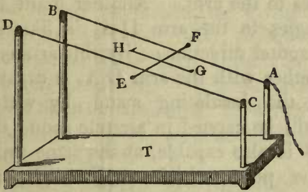
Fig. 16.



stantly electrified by a machine. Let each of the four arms of the wires be terminated by a point in a horizontal direction at right angles to the wire, each point being turned in the same direction as represented in the figure. When the electricity comes from the conductor to the wires, it will escape from the wires at these four points respectively, and the force with which it leaves them will be attended with a proportionate recoil, which will cause the wire to spin rapidly on the centre E.

(118.) An apparatus supplying another illustration of this principle is represented in *fig.* 17. A square wooden stand T has four rods of glass inserted at its corners, the rods at one end being less in height than those at the other. The tops of these rods having metal wires A B and C D stretched between them, across these wires another wire E F is placed, having attached to it at right angles another wire G H having two points turned in opposite directions at its extremities, so that when G H is horizontal, these two points shall be vertical, one being presented upwards, and the other downwards. A chain from A communicates with a conductor, kept constantly electrified by a machine.

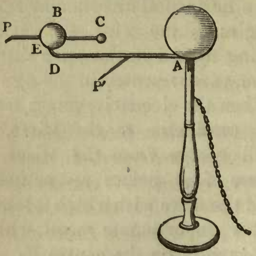
Fig. 17.



The electricity coming from the conductor by the chain passes along the system of wires, and escapes at the points G and H. The consequent recoil causes the wire G H to revolve round E F as an axis, and thereby causes E F to roll up the inclined plane.

(119.) An apparatus called the *electrical* orrery is represented in *fig.* 18. A metallic ball A rests upon an insulating stand by means of a cap within it, placed upon a fine metallic point, forming the top of the stand. From the ball A, an arm D A proceeds, the extremity of which is turned up at E, and formed into a fine point. A small ball, B, rests by means of a cap on this point, and attached to it are two arms, extended in opposite directions; one terminated with a small ball C, and the other by a point, P, presented in the horizontal direction at right angles to the arm. Another point P′, attached at right angles to the arm D A, is likewise presented in the horizontal direction. By this arrangement the ball A, together with the arm D A, is capable of revolving round the insulating stand, by which motion the ball B will be carried in a circle round the ball A. The ball B is also capable, at the same time, of revolving on the point which supports it, by which motion the ball C will revolve round the ball B in a circle. If electricity be supplied by the chain to the apparatus, the balls A and B, and the metallic rods, will be electrified, and the electricity will escape at the points P and P′. The recoil produced by this escape will cause the rod D A to revolve round the insulating pillar; and, at the same time, the rod P C, together with the ball B, to revolve on the extremity of the arm D A. Thus, while the ball B revolves in a circular orbit round the ball A, the ball C revolves in a smaller circle round the ball B. The motion resembling that of the moon and earth with respect to the sun.

Fig. 18.



CHAP. VI.

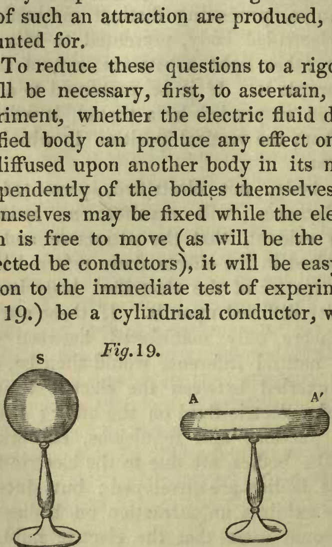
INDUCTION.

(120.) In all the phenomena which have been hitherto considered, the electricity developed on bodies has been educed either by the contact of two bodies, accompanied by friction, or by the mere contact of an electrified body with one not electrified. Among the earliest manifestations, however, of the phenomena of electricity, effects were rendered apparent, which proved that the agency of electricity did not require absolute contact; but, on the contrary, that it operated at definite distances, producing distinct mechanical effects. Thus an electrified body, presented to bits of paper, feathers, or other light substances, caused these latter to move towards it. If it be presented to a small ball not electrified suspended by a thread, it will draw the ball aside from the vertical position in which it would naturally rest.

Since a body, not electrified, presented to these various substances, will manifest no attraction for them, it is evident, that the attractive and repulsive forces exhibited in the effects above referred to are due, not to the matter of the electrified body itself, but to the electricity diffused upon it. If these attractions or repulsions were only manifested between electrified bodies, the natural inference would then be, that these forces are exerted between the electric fluid on one body, and the electric fluid on the other; and that the apparent attractions and repulsions, exhibited in the motion of the bodies, are due to the electric fluid with which these bodies are enveloped; but since an electrified body exhibits an attraction on bodies not electrified, it would seem that the electric fluid, diffused over an electrified body, exerts an attraction on the matter of bodies not electrified. Such an inference, on the other hand, is discountenanced by the ascertained fact, that the electricity diffused on an electrified body is retained there, not by any proper attraction existing between the electric fluid and the matter of the body, but merely by the pressure of the surrounding atmosphere. If the electric fluid have no attraction for the matter of the body which it envelopes, it would be unreasonable to suppose that it would have an attraction for the more distant matter of another body. The electric fluid diffused upon the surface of an electrified pith ball, suspended by a silken thread, is proved to have no attraction for the matter composing that pith ball. How then, it may be asked, can it be assumed to have an attraction for another precisely similar pith ball, similarly suspended in its neighbourhood? Yet the *effects* of such an attraction are produced, and ought to be accounted for.

(121.) To reduce these questions to a rigorous analysis, it will be necessary, first, to ascertain, by immediate experiment, whether the electric fluid diffused on one electrified body can produce any effect on the electric fluid diffused upon another body in its neighbourhood, independently of the bodies themselves. As the bodies themselves may be fixed while the electric fluid upon them is free to move (as will be the case if the bodies selected be conductors), it will be easy to bring this question to the immediate test of experiment. Let A A′ (*fig.* 19.) be a cylindrical conductor, with hemi-

Fig. 19.



spherical ends, supported by a pillar of glass, or other insulating substance; let S be a sphere formed of a conducting substance, and likewise supported on an insulating pillar; let the centre of the sphere S be so placed, that it shall be in the direction of the geometrical axis of the conductor A A′. Let the conductor and the sphere be both strongly electrified with the same kind of electricity, for example, with positive electricity. If the conductor be examined by means of the proof plane and the electrometer, it will be found that the electricity is not uniformly diffused upon it, but that its depth is least at the extremity A, nearest the sphere, and that it increases gradually towards the electrical A′, most remote from the sphere.

If the sphere S be now gradually removed from the conductor, its centre however being still kept in the direction of the axis of the conductor, the distribution of the electricity upon the conductor will undergo a gradual change, its density towards the extremity A being progressively increased while its density towards the extremity A′ is progressively diminished. If, on the other hand, the sphere S be moved towards the conductor, the density of the electricity towards the extremity A will be diminished, while the density towards the extremity A′ will be increased.

If the sphere S be removed altogether from the neighbourhood of the conductor, or if the sphere be deprived of its electricity, the electricity of the conductor A A′ will instantly resume that uniform distribution which, under ordinary circumstances, it takes, and every part of its surface examined by the proof plane will indicate electricity of the same density. If the sphere S be again electrified, and brought near to A A′, the uniform distribution of the electricity on A A′ will again be destroyed, and the electricity will, as before, be accumulated towards the extremity A′, most remote from the sphere S.

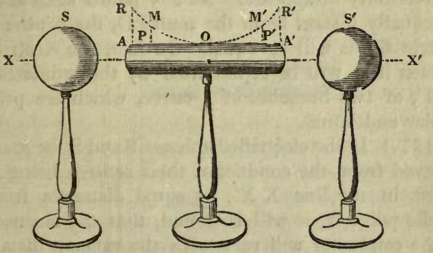
(122.) The result of this experiment indicates a repulsive action, exercised by the electric fluid of the sphere S, upon the electric fluid diffused upon the conductor A A′. If the sphere S, instead of being charged with positive electricity, were equally charged with negative electricity, and, instead of being presented to the extremity A, were presented to the extremity A′, precisely the same effects would ensue. The electricity on A A′ would be accumulated towards A′, and its densities on different points of the conductor would increase from A to A′. The result of such experiment would indicate an attractive force exerted by the negative electricity of the sphere upon the positive electricitv of the conductor.

(123.) We have supposed that the conductor A A′ was in this case charged with positive electricity. The same results however would be obtained, *mutatis mutandis*, if it were charged with negative electricity. In that case, the negative electricity would be accumulated towards the extremity most remote from the sphere charged with negative electricity, or towards the extremity nearest the sphere when charged with positive electricity.

(124.) All these experiments lead to the conclusion, that the attractive and repulsive forces which are manifested between electrified bodies belong to the electric fluid diffused upon bodies, and that similar electric fluids repel each other, while dissimilar electric fluids attract each other. This principle will be further illustrated by phenomena, which we shall hereafter explain.

(125.) If the attractions and repulsions which have been referred to be ascribed to the electric fluids with which bodies be invested, and not to the bodies themselves, the motions imparted to bodies not electrified by the near approach of electrified bodies still demand explanation; for if it be true that the electric fluids only attract and repel themselves, and that the bodies neither exercise nor suffer attraction or repulsion, how, it may be asked, can the electric fluid with which any body is invested, produce the effects of attraction on a body which is free from all electricity?

Fig. 20.



(126.) To arrive at an explanation of this difficulty, it will only be necessary to examine carefully what will happen to an insulated conductor, *not electrified,* when an electrified body is brought near it in such a position, that, were it free to move, and sufficiently light, it would be attracted in the same manner as a pith ball, not electrified, is attracted by an electrified body. For this purpose, let S and S′ (*fig.* 20.) be metallic spheres supported on pillars of glass, and let A A′ be a conductor also insulated; let these bodies be in the first instance free of all electricity, which may be insured by putting each of them for a moment in communication with the earth by touching them; in addition to which, each of them may be tested by the proof plane, and the electrometer in the usual manner. Let the spheres S and S′ be now strongly and equally charged, the one S with positive, and the other S′ with negative electricity, and let the conductor A A′ be placed between them, as represented in the figure, so that the centres of the spheres shall be placed in the prolongation of the geometrical axis X X′ of the conductor, and at equal distances from its middle point O. If the conductor be now examined by the proof plane and the electrometer, it will be found to be no longer in its natural state, or free from electricity, as it was before the spheres S and S′ were electrified. On applying the proof plane to different points throughout its length, it will be found, that the only part which is free from electricity is its centre O; that the half of the conductor, extending from O to A, is electrified, and that its electricity is negative; and that the other half of the conductor, extending from O to A′, is also electrified, and that its electricity is positive. The intensity of the opposite electricities at the extremities A and A′ will be equal, and the intensities will gradually diminish from the extremities to the centre O, where all electricity disappears. At any points such as P and P′, equally distant from the centre O, the depths of the electric fluids will be equal. In fact, the electric state of each half will be represented by the ordinates P M, P′ M′, of two branches of a curve, which are precisely similar and equal.

(127.) If the electrified spheres S and S′ be gradually removed from the conductor, their centres being maintained in the line X X′, at equal distances from the middle point O, it will be found, that the electric state of the conductor will vary with the varying distance of the centres of the spheres from its middle point. The middle point O will still be free from all electricity, while the conductor on each side of it will still be electrified, with contrary electricities, and the electric depths at equal distances from O will still be equal; but the actual electrical depth at any given distance from O will be diminished by the increase of distance of the spheres from O. In fact, as the spheres recede from O, in opposite directions, being kept however at equal distances from it, the curve, whose ordinates represent the densities, will become less and less concave, taking successively the forms in figures 21. and 22., until at length, when the electrified spheres are removed indefinitely, the conductor recovers its natural state, and is free of all electricity.

On the other hand, if the sphere S and S′ be moved in the contrary direction, and made to approach the conductor, the accumulation of electricity towards the extremities of the conductor will be increased, and the curve representing the electrical densities will take the form represented in figure 23.

Fig. 21.

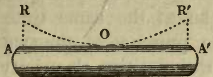


Fig. 22.

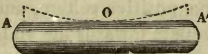
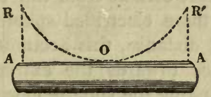


Fig. 23.

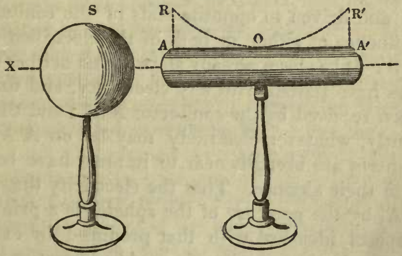


(128.) It is impossible not to perceive how strongly these phenomena suggest the existence of the two electric fluids in equal quantities, and uniformly distributed over a body in its natural state. In the experiments here described, no electricity has been imparted to the conductor A A′ by either of the spheres S and S′; for if these spheres be examined after the experiment, by means of the proof plane and the electrometer, they will be found to have lost no electricity, except what was dissipated by the air. Neither has the permanent electrical state of the conductor been changed, for in removing the spheres from it, it will be found to be in its natural state, and free from all electricity. On the other hand, the result of the experiment is exactly what would have been anticipated, if we could have conceived the conductor A A′ to be at the same time charged with equal quantities of positive and negative electricity; for, when it was charged with positive electricity, the repulsion of the electricity of the sphere S caused the electricity to accumulate towards the extremity A′, and the attraction of the negative electricity of the sphere S′ produced a like effect. When the conductor was charged with negative electricity, the attraction of the positive electricity of the sphere S caused the negative electricity of the conductor to accumulate towards the extremity A, while the repulsion of the negative electricity of the sphere S′ produced the same effect. It is evident, therefore, that if equal quantities of both kinds of electricity be at the same time diffused upon the conductor, the presence of the two electrified spheres would cause the positive electricity to accumulate towards the end nearest the negative sphere, and most distant from the positive sphere, and the negative electricity to accumulate towards the end nearest the positive sphere, and most distant from the negative sphere. If the action of these electrified spheres increase with the diminution of distance, this accumulation of the opposite electricities towards the extremities will be augmented by bringing the spheres closer to the conductors, and will be diminished by removing them farther from it. These are precisely the effects which take place, and the conductor A A′ in its natural state, therefore, comports itself under the various circumstances above mentioned *exactly as a conductor would do charged with equal quantities of the contrary electricities.*

(129.) In these experiments we have supposed that the two spheres S and S′ are maintained throughout all their changes of position at equal distances from the conductor A A′, and on the supposition that the two spheres under like circumstances produce like effects on the positive and negative electrical principles diffused upon the conductor, it might be expected that the neutral point O would be placed, as in fact it has been found to be, exactly in the middle of the conductor; but if the two spheres equally charged with opposite electricities be not symmetrically placed with respect to opposite ends of the conductor, this similar distribution of opposite electricities on either side of the centre of the conductor will not be expected. If one of the spheres, S′ for example, be gradually removed from the conductor, the distribution of the contrary electricities will no longer be symmetrical with respect to the centre of the cylinder, and the neutral point O will be removed from the centre of the cylinder to a position nearer the extremity A; and that portion of the cylinder on which negative electricity is educed, will be less than half its length.

(130.) To carry this supposition to its extreme length, let it be supposed that the sphere S′ is removed altogether from the conductor, which is therefore left under the sole influence of the sphere S, in the present case supposed to be positively electrified. If the state of the conductor A A′ be now examined by the proof plane and the electrometer, the neutral point O will be found, as represented in figure 24., to be between the centre of the cylinder and the extremity A; the cylinder from O to A will be negatively electrified, the electric density increasing in like manner. The electric densities being as before represented by the ordinates of a curve, the state of the cylinder will be shown by the curve in the figure.

Fig. 24.



If the sphere S, acting thus alone upon the conductor A A′, be gradually moved towards X, so that its distance from the conductor is progressively increased, the effects of its attraction and repulsion are gradually diminished, and accordingly it is found by experiment that the neutral point O, which by this inequality was transferred from the centre towards A, is again removed towards the centre, and approaches it more nearly as the distance of S from the conductor is augmented.

We have here supposed that the sphere S is charged with positive electricity. Corresponding results would be obtained if it had been electrified negatively. In that case, the electricity from A to O would have been positive, and the electricity from A′ to O would have been negative: in all other respects the effects would have been the same.

(131.) All these results tend to establish the position that a conductor, such as A A′ in its natural state, and apparently divested of all electricity, holds nevertheless upon it the two opposite electric principles which have been denominated positive and negative; and that these two principles are decomposed, and separated, and driven to opposite ends of the conductor by the influence of either or both of the electrified spheres S and S′. It has been already shown, that neither of these spheres have parted with any electricity, and that none has been received by the conductor A A′; and that, consequently, whatever electricity may be on A A′ when the spheres are brought near to it, must have been also on it in their absence. That the electricity thus educed on A A′ by the presence of the spheres is a principle in all respects identical with that produced by excitation or communication, admits of easy demonstration. When the opposite extremities of the conductor A A′ are enveloped with contrary electricities by the proximity of the sphere S, let an insulated conductor, such as a sphere of metal supported on a glass pillar, be brought into contact with A′, it will immediately become charged with positive electricity, and when removed will produce the same effect as the electrified positive conductor of an electrical machine. If, after this has been done, the sphere S be removed from the neighbourhood of the conductor A A′, it will be found that the conductor A A′ is charged with negative electricity, and will produce the same effects as the negative conductor of an electrical machine.

If the sphere, which by contact with the extremity A′ became positively electrified, be now again brought in contact with the conductor A A′, the positive electricity which had been taken from the conductor will be restored to it, and it will return to its natural state.

(132.) Since an electrified insulated conductor, brought near to another insulated conductor in its natural state, will cause the latter to become electrical, having contrary electricities on opposite sides of it, the electricities thus developed in the conductor will be capable of acting in the same manner on another conductor contiguous to it, and the latter on a third, and so on. In the illustrations of these principles which have been here given, we have, for the convenience of explanation, assigned certain forms to the bodies under consideration; but the same effects will be produced, and the same reasoning may be applied, whatever may be the form of the bodies. Let S, as before, be an insulated conductor electrified positively, and let A, A,′ A″, A‴, &c. be a series of insulated conductors disposed contiguous to each other, but not in contact, as

A A′ A″ A‴ A⁗,

these being in their natural state. Now let S, electrified positively, be placed to the left of A, and let the positive electrical state be expressed by +, and the negative by −; the electrical state of the whole series produced by the position assigned to S will be as follows:

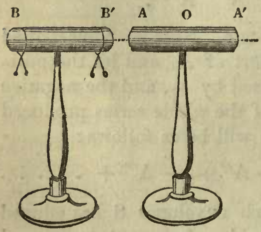
+S+, −A+, −A′+, −A″+, −A‴+ . . . . .

The positive electricity which envelopes S has educed negative electricity on the side of A next to it, and positive electricity on the opposite side.

The positive electricity thus educed on the opposite side of A, educes negative electricity on the adjacent side of A′, and positive electricity on the opposite side. Again, the positive electricity thus educed on the opposite side of A′ has educed negative electricity on the adjacent side, and positive electricity on the opposite side of A″, and so on throughout the series; negative electricity being evolved on the sides of the conductors nearest to S, and positive electricity on the opposite sides.

(133.) As an electrified body, such as the sphere S, produces so important an action on a body in its natural state, it may be expected in conformity with the general principles and analogies of physics, that a reciprocal effect would be produced, and that the electrified body S itself would suffer some corresponding effect from the influence of the electricity which it has evolved on the conductor contiguous to it. Experiment accordingly confirms the anticipation suggested by these analogies; but in order to render the explanation of this reaction more simple and more pointedly illustrative of the theoretical principles which have been raised upon these phenomena, we shall here consider the case in which the electrified body has a form similar to that of the conductor on which it acts.

Fig. 25.



Let us then suppose that B B′ (*fig.* 25.) is an insulated cylindrical conductor, with hemispherical ends strongly charged with positive electricity, and let a pair of pith balls be suspended from each extremity of it, connected by linen threads attached to rings of wire surrounding the conductor. Since the threads and wire are conductors of electricity, the pith balls will share the electricity of the conductor, and will diverge from each other to a distance proportionate to the electric density of the conductor at the points at which they are attached. The balls will diverge equally, indicating the uniform diffusion of the electricity of the conductor. Let a similar and equal conductor, A A′, in its natural state, be so placed that its geometrical axis shall be in the same straight line with that of the electrified conductor B B′, and let it be gradually moved towards B B′. As it approaches B B′, the opposite electricities will be educed upon its surface, and distributed in the same manner as already described with respect to the conductor A A′ (*fig.* 24.), when brought near the electrified sphere S. The negative electricity is accumulated at the end A, and the positive electricity at the end A′, the neutral point O being nearer to A than to A′. If the state of the pith balls upon the conductor B B′ be examined, it will be found that, as soon as any sensible evolution of electricity has taken place upon A A′, the divergence of the balls near the extremity B′ will be increased, while the divergence of those near the extremity B is diminished, and according as the distance of the conductor AA′ from BB′ is lessened, the divergence of the balls near B′ is augmented, and the divergence of those near B is diminished. These effects indicate a gradually increasing accumulation of the positive electricity of BB′ towards the extremity B′.

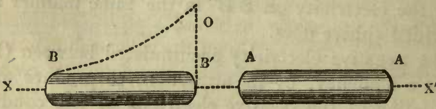
This is nothing more than might have been expected. The electricity which has been educed on A A′, acts upon the electricity on B B′ in the same manner as an electrified sphere does.

The negative electricity accumulated between O and A has a tendency, by its attraction, to produce an accumulation of the positive electricity of the conductor B B′ towards the extremity B. The positive electricity accumulated from O to A′ has a contrary tendency, by reason of its repulsion; but its effect is diminished by its greater distance from B′, and the two electricities of the conductor AA′ produce an attraction on the positive electricity of the conductor B B′ proportionate to the excess of the attraction exercised by the negative electricity accumulated from O to A above the repulsion of the positive accumulated from O to A′. This excess of attractive force, acting on the positive electricity with which BB′ is charged, produces the accumulation towards B′, which causes the increased divergence of the one pair of balls and the diminished divergence of the other.

(134.) But another important phenomenon contributes to increase this effect. The excess of the attraction of the negative electricity on the conductor A A′ affects not only the positive electricity with which it has been charged, but, in addition to this, is attended with the same effect as would be produced upon it by that attraction if it were in its natural state. These effects would be, as has been already explained, the evolution of positive electricity towards the extremity B′, and the negative electricity towards the extremity B. The former of these effects tends to increase the quantity of positive electricity drawn to the end B′, while the latter diminishes the depth of the portion which remains at the end B. In the present case, this part of the effect of the electricity educed on the conductor A A′ cannot be rendered apparent, since the negative fluid evolved towards the extremity B is neutralized by a portion of the positive fluid with which the conductor has been charged.

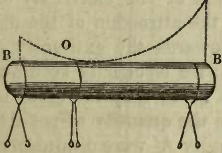
(135.) To render it apparent, let the conductor B B′ (*fig.* 26.) be *feebly* charged with positive electricity.

Fig. 26.



In the absence of the conductor A A′, the depth of electricity on every part of B B′ will be the same, and the two pairs of pith balls will be equally divergent. Let the conductor A A′ in its natural state be now made to approach B B′ slowly from a distance, being moved in the direction X′X. As it approaches the divergence of the balls near the extremity, B′ will gradually increase, while the divergence of the other balls will gradually diminish. When it has come within a certain distance of B B′, the balls near B will have collapsed, while the divergence of the balls near B will be still more augmented. In this position of the conductors, therefore, the extremity B is reduced to its natural state, while the conductor extending towards B′ is electrified positively, the electric density continually increasing, as represented by the curve (*fig.* 26.), from B to B′. This effect is produced not merely by the attraction of the electricity developed on the conductor A A′ acting on the positive electricity with which the conductor B B′ is charged; for if that were the case, the further approach of the conductor A A′ towards the conductor B B′ would only produce a continued motion of the positive electricity of B B′ towards the extremity B′, and a portion of the conductor B B′ of more or less extent at the extremity B, would be reduced to its natural state, so that pith balls suspended any where upon it would collapse by their gravity. Such, however, will not be the case; for if the conductor A A′ be moved still nearer to B B′, the balls near the extremity B, which had before collapsed, *will again diverge*, and if another pair of pith balls be moveable on the conductor, a point O (*fig.* 27.) will be found near the extremity B, where the balls will collapse, and where the conductor therefore is in its natural state. The divergence of the balls near B, proves that the conductor between O and A is electrified, and if it be examined by means of the proof plane and the electrometer, it will be found to be charged with negative electricity of gradually increasing density from O to A, while the conductor from O to A′ is charged with positive electricity of gradually increasing density.

Fig. 27.



(136.) It is evident, therefore, that the effect of the electricities developed on A A′ is twofold; *first*, it attracts the positive electricity with which the conductor B B′ is charged from B towards B′: *secondly*, it developes on B B′ the opposite electrical principles, in the same manner as they are developed on a conductor in its natural state by the proximity of a conductor positively electrified. The combination of these two effects produces an electrical state of the conductor B B′, which is dependent on the distance of the conductor A A′ from it. Beyond a certain distance B B′ is positively electrified. When the conductor A A′ is brought to that particular distance, the end B of the other conductor is reduced to its natural state, the electricity from B to B′ being positive, and of gradually increasing density; when the conductor A A′ is brought nearer to B B′ than that particular distance, a neutral point O (*fig.* 27.) is established between B and the middle of the conductor where the conductor is in its natural state, and which divides it into two portions oppositely electrified, O B being negatively electrified, and O B′ being positively electrified. The position of the neutral point O will depend on the distance of the conductor A A′ from B B′; the less this distance is, the nearer the point O will be to the centre of the conductor.

(137.) It appears from what has been explained, that the effect of the approach of the conductor A A′ upon the distribution and development of the electricity on B B′ depends on the excess of the attraction of the negative electricity accumulated towards the extremity A above the repulsion of the positive electricity accumulated towards the extremity A′. It may therefore be expected, that if by any means the quantity of positive electricity collected at the extremity A′ were diminished, and still more if that electricity were altogether abstracted, the effects of the conductor A A′ upon B B′ would be augmented. This may be easily tested by experiment: Let us suppose the two conductors to be placed under the circumstances represented in *fig.* 35., in which the conductor B B′ is electrified positively throughout its whole length, the electric density gradually increasing towards the extremity B′, as indicated by the comparative divergence of the pith balls. Let a small insulated spherical conductor be now brought in contact with the conductor A A′ at the extremity A′, and removed from it. Immediately the divergence of the pith balls near B′ will be observed to be increased, and the divergency of those near B diminished, indicating a further movement of the positive electricity from B towards B′. If the spherical conductor which was brought into contact with A′ be examined, it will be found to be charged with positive electricity. The result of the experiment is therefore easily explained. A portion of the positive electricity, which was collected near A′, has been removed. The negative electricity near A now exceeds the positive electricity near A′, and this has given increased power to the electricity developed upon A A′ over the electricity diffused upon B B′, and a greater quantity of the latter has been consequently drawn from B towards B′, producing, as we have seen, an increased divergence of one pair of balls, and a diminished divergence of the other pair.

(138.) But the effects of this change in the electrical state of A A′ do not end here. The increased accumulation of positive electricity towards B′ is attended with a corresponding means of attraction excited upon the negative electricity of A A′, and of repulsion upon its positive electricity. An augmented development of both these principles is the consequence, and this again re-acts on the electricities of B B′; and in this manner a reciprocal series of effects is produced, which continue until the mechanical equilibrium between the electricities of the two conductors, disturbed by the abstraction of the electricity from A′ by the contact of the spherical conductor has been re-established. In order to render this process intelligible, the series of effects has been here described as if a definite time were occupied in their production. Such, however, is not the case. They are, in fact, completed instantaneously, and the moment the spherical conductor has touched the extremity A the pith balls on B B′ assume a new divergence, which they maintain.

(139.) If the spherical conductor, having been discharged, be again brought in contact with A′, like effects ensue. The pith balls near B′ further increase their divergence, and the divergence of those near B is diminished, and the same process may be repeated with the same effects. To carry this principle to its extreme limits, let the extremity A′ be put for a moment in communication with the earth, by being touched by a conductor which is not insulated; immediately the whole of the positive electricity accumulated near A′ will pass away, and the negative electricity accumulated near A will take effect with undiminished force on the electricity of the conductor B B′. An increased divergence of the balls near B′ will take place, and the balls near B will either be diminished in their divergence, or will collapse, or finally will diverge with negative electricity, according to the quantity of positive electricity with which the conductor B B′ has been originally charged. A reaction, similar to what has been already described, takes place between the electricities on the two conductors, until their mutual attractions and repulsions are restored to a state of equilibrium.

To render these effects more easily intelligible, we have supposed the conductor B B′ to be originally charged with positive electricity. The results, however, would have been the same, *mutatis mutandis,* had it been charged with negative electricity.

(140.) The important electrical phenomena of the development of electricities on bodies in their natural state by the near approach of bodies already electrified, which have formed the subject of the present chapter, have been denominated by English electricians *induction,* and when a body is rendered electrical by the presence of an electrified body not in contact with it, it is said to be *electrified by induction,* and the electricity developed upon it called *induced electricity.* The effects of induction will be still more fully developed in the following chapter, when the theories which have been proposed to connect together and explain the phenomena of electricity will be discussed. In a series of conductors (such as A A′ A″, described in § 132.), in which electricity is educed by the influence of a positively electrified conductor S placed before A, if the positive end of the conductor A''' be put in communication with the earth, so as to discharge its positive electricity, an increased development of electricity will take place on the preceding conductor A'', upon the principles already explained. This will produce, by the same principles, a corresponding increase of electricity on the conductor which precedes it, and so on throughout the series, so that the first conductor A, having an increased development of negative electricity on the side presented to S, will produce an increased accumulation of positive electricity on the side of S presented towards it.

CHAP. VII.

THEORY OF ELECTRICITY.

(141.) In any branch of natural science, where the facts collected in the careful observation of the operations of nature, and by accurate and well-directed experiments, become sufficiently numerous and varied to show traces of general laws, it is the province of the philosopher to form a theory, which, by assigning adequate general causes, may embrace, under a few comprehensive theorems, all the various phenomena which observation and experiment have supplied. By such means, those who prosecute scientific researches are placed in a condition to foretell what will happen under any supposable physical conditions; and the accordance of the event with such predictions, supplies the most legitimate proof of the validity of the theory on the principles of which such predictions were made.

It has happened in almost every branch of natural science, that more than one theory has been propounded to account for the phenomena; and, in many cases, rival theories have maintained their ground, supported by a body of partisans, during the progressive advancement of the science, under the increasing labours of those whose vocation is to observe and collect facts and phenomena rather than generalise them. No hypothesis can be expected to gain any general or permanent acceptance, which does not afford a satisfactory explanation of the more striking phenomena, and obvious appearances, for the explanation of which it has been proposed. In cases, therefore, where the community of science has been divided between two contending theories, more especially in modern times, when inductive science is so well understood, it ought to excite no surprise that both such theories afford explanations equally plausible and satisfactory for all the ordinary phenomena comprised in the department of science to which they extend. It is not, then, by the account which they render of these prominent effects that the claims of conflicting hypotheses can be decided. If they had not been adequate to the explanation of such appearances, they never could have obtained such an extensive assent as to raise any question respecting their validity. Such hypotheses can only be tested in two ways: *first,* by exacting from them a clear and consistent account of phenomena developed *after* the theory itself had been proposed, and which were not foreseen by those who propounded it; and, *secondly,* by deducing from it, not merely a *general* account of the phenomena which will be produced under any given physical conditions, but by exacting from it a rigorous *numerical* and *quantitative* estimate of the effects, and by comparing such estimate, so deduced from the theory, with the actual numerical and quantitative account as obtained from experiment and observation. If the discrepancy between the numbers and quantities furnished by the theory and by observation exceed the possible amount of the errors of observation, and still more, if the principles of the theory afford no means whatever of reducing the effects to numerical calculation, such theory must be rejected as insufficient. If, on the other hand, it be found that an hypothesis, capable of affording a clear and satisfactory explanation of the general nature of all the phenomena, as well those which were known to its proposers, as those which observation and experiment subsequently developed; if it also supply the means, by calculation and reasoning, of predicting other phenomena to which experiment and observation have not yet been directed, and that the effects already produced under the prescribed conditions have been found to be in strict accordance with such predictions; if, moreover, by the application of the principles of analytical calculation, the *numerical* and *quantitative* amount of *all* the phenomena are capable of being deduced from such hypothesis, and the difference between such numerical results, and the actual numerical quantities obtained by observation and experiment, do not exceed the possible amount of the errors of observation; — then such theory must be regarded as proved, and ought, by the principles of inductive philosophy, to be assented to and received, until some phenomena shall arise of which it is incapable of giving a satisfactory account.

(142.) Two theories have been proposed for the explication of the phenomena of electricity. That which, until within a few years, has been most generally embraced in this country, originated with Dr. Franklin, by whose labours this department in physics has been so highly enriched. The other hypothesis is usually ascribed to Dufay; but it may be more properly attributed to Mr. Robert Symmer. Int. (90.)

Both these theories agree in ascribing the phenomena of electricity to a material substance, endowed with the most perfect fluidity, the molecules of which are distributed on the surfaces of bodies. The properties of a fluid are irresistibly suggested by all the most striking phenomena of electricity. The extreme facility with which electricity diffuses itself on conductors, its rapid escape when relieved from the pressure of the surrounding air, the perfect mobility with which its particles transfer themselves from conductor to conductor, and by which they combine and separate, all concur in suggesting the notion of fluidity.

In the theory of Symmer, however, the existence of two independent fluids is assumed, the vitreous and the resinous, or, according to the other nomenclature, the positive and the negative. Each of these fluids is self-repulsive, its particles tending to separate from each other by an elastic force like that of atmospheric air. Thus, if a certain quantity of either of those fluids, the positive for example, be introduced upon a metallic sphere, where its motion is unobstructed, it will instantly diffuse itself by its self-expansive or elastic force over the entire surface, on which it will form a thin stratum. If we conceive the sphere to be increased in magnitude, the electricity will still diffuse itself uniformly over the enlarged surface, in a stratum which is thinner in proportion as the surface over which it is spread is augmented. If the pressure of the air which surrounds it be removed, the electric fluid is altogether dissipated. All these effects, the reality of which are established by observation, are indications of the elastic or self-expansive property.

(143.) But the two fluids, the positive and the negative, whose particles respectively have this repulsive action among themselves, have towards each other a mutual attraction. The various phenomena of induction, described in the preceding chapter, sufficiently manifest this reciprocal attraction. In the theory to which we now refer, the law of attraction and repulsion of these fluids is assumed to be similar to that which was manifested between electrified bodies, as explained in Chapter II.; and the hypotheses which forms the basis of the theory may be accordingly announced in the following terms:—

Each of the two electrical principles has the properties of a perfectly elastic fluid ; its molecules enjoy a perfect mobility, are reciprocally repulsive of each other, and attractive of the molecules of the other fluid. These attractions and repulsions diminish in the same proportion as the square of the distance increases, and at equal distances the attraction is equal to the repulsion.

(144.) Bodies, in their natural state, are considered as having equal quantities of these two fluids diffused upon them, the molecules of which, by attracting each other with equal and opposite forces, are maintained in a state of equilibrium. When a body is electrified with positive electricity, for example, it is considered as having diffused upon it a quantity of the positive electric fluid, in addition to the combination of the two electricities which would be diffused upon it in its natural state; and, when a body is negatively electrified, it is considered as having a quantity of the negative electric fluid diffused upon it, having likewise the combination of electricities which characterise the natural state.

(145.) When an electrified body is brought near an insulated conductor, which is in the natural state, the electric fluid with which the former is charged acts by attraction and repulsion upon the two fluids which are naturally combined upon the conductor. It acts by repulsion on the molecules of fluid of its own name, and by attraction on those of the contrary name. Thus, if the electrified body be charged with negative electricity, it attracts the molecules of the positive fluid, and repels those of the negative fluid on the conductor. By this means, it separates or decomposes a quantity of the combined fluids on the conductor, drawing the positive molecules to the side next itself, and repelling the negative molecules to the opposite side. The quantity of natural electricity thus decomposed is proportional to the force excited by the electrified body upon the conductor, which force depends partly on the quantity of the electricity with which the electrified body is charged, and partly on its distance from the conductor.

It will be easy, by following out these views, to perceive how the various effects of induction detailed in the last chapter are accounted for by this theory.

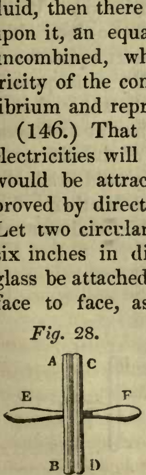
When electricity is excited by the friction of two bodies, the natural electricity upon one or both of them is decomposed by some forces or powers brought into operation by the friction, and the molecules of the positive fluid adhere to one of the two bodies so submitted to friction, while those of the other fluid adhere to the other body.

When an insulated conductor charged with positive electricity is brought near to another conductor not insulated, that other conductor is regarded as a part of the entire globe of the earth, forming one great conductor. The positive electricity with which the insulated conductor is charged, as it approaches the conductor not insulated, decomposes by its attraction and repulsion a portion of the combined electricity of the entire globe, and attracts to the part of the conductor nearest to it a portion of negative electricity. When the conductors are brought so near together that their mutual attraction produces such an accumulation of contrary electricities at the parts contiguous to each other that the pressure exceeds that of the atmosphere, they rush towards each other, and combine so as to neutralise each other, and it may be considered that the positive electricity of the electrified conductor escapes to the earth, where it combines with an equal portion of negative electricity.

It may be here observed that the supposition that the total quantity of negative electricity existing on the globe is equal to the total quantity of positive electricity, involves the consequence that whenever there is any quantity of either electricity uncombined, as is the case when an insulated conductor is charged with either fluid, then there will be on the earth, or on some body upon it, an equal quantity of the other electricity also uncombined, which by combination with the electricity of the conductor, will restore the electrical equilibrium and reproduce the natural state.

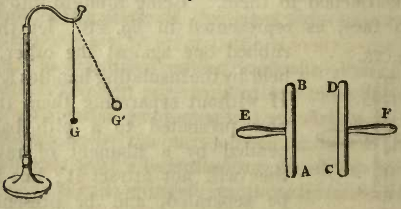
(146.) That the combination of the two opposite electricities will manifest no attraction on a body which would be attracted by either acting alone, may be proved by direct experiment in the following manner. Let two circular discs of plate glass be formed about six inches in diameter, and let insulating handles of glass be attached to them. Being brought into contact face to face, as represented in *fig.* 28., let them be rubbed one against the other, being held by the insulating handles E and F. If without separating them they are now presented to a pith ball suspended by a filament of raw silk, they will not attract it; but if they be separated, and be presented se-

Fig. 28.



parately to it, they will attract it. They are therefore both electrified, and it is easy to show that they are *oppositely* electrified; for if they be presented separately to an electrified pith ball, one of them will attract and the other will repel it. Since, however, the discs, when in contact, produce no effect upon the electrical pendulum in its natural state, it is clear that the two electricities, though developed on the surfaces of the glass discs, and not naturally combined, nevertheless neutralise each other's effects; the attraction which either would exert on the pith ball being counteracted by the effect of the other. The positive electricity developed upon the discs has a tendency to decompose the natural electricities of the pith ball, drawing its negative electricity to the side next to the discs, and driving its positive electricity to the opposite side; while on the contrary the negative electricity of the discs has a tendency to draw the positive electricity of the ball to the side next the discs, and to drive the negative electricity to the opposite side. When the faces of the discs are in contact, the two electricities being equally distant from the ball exert equal forces tending to produce these effects, and they consequently neutralise each other; but it is easy to show that if they were presented to the ball at different distances, they would produce an effect in virtue of the difference of their attractions, and that this effect would gradually diminish as the discs would approach each other. Let G (*fig.* 29.) be a pith ball suspended in the usual manner,

Fig. 29.



and let A B be one of the discs presented with its insulating handle E towards the pith ball; the electricity excited upon its surface acting through the glass will draw the ball from the vertical position G to the position G′. Let the other disc C D be now presented with its face towards A B. As it is advanced towards A B, the ball will gradually descend from the position G′ to the position G, arriving at the position G at the moment when the face of the disc C D comes into contact with that of the disc A B.

(147.) Such, in general terms, is the hypothesis of two fluids propounded by Symmer and Dufay, and which, as we shall presently show, has by the aid of the higher principles of mathematical analysis afforded satisfactory solutions for all the phenomena of electricity to which the present powers of mathematical science allow it to be applied. We shall now briefly explain the Franklinian theory.

This theory assumes the existence of a single electric fluid, self-expansive and possessing perfect fluidity and mobility. The molecules of this fluid are supposed to attract and be attracted by the constituent particles of all material substances. The attractions however exerted between it and different substances are different, and its attraction even for the same substance is variable, according to the various changes which the physical properties of such substance may undergo. A body is supposed to be in its natural state when it contains upon it as much of the electric fluid as satisfies its attraction. If it contain *more*, such excess is free, and the body is positively electrified. If it contain *less*, the body is said to be negatively electrified. Excitation, therefore, takes place when there is either more or less electricity on the body than is adequate to the saturation of its existing attraction ; but not to incur the risk of unintentionally misstating a theory to the validity of which we do not assent, we shall borrow from a modern author, a partisan of the theory, an outline of it, together with a few experimental illustrations in support of it

"Electrical excitation may be thus effected: the bodies employed have each a certain quantity of the electrical fluid proportionate to their natural attraction for it. This they retain, and appear unelectrified so long as they remain in their natural state. Now, if two such bodies are brought into contact, their natural attractions are altered; one of them attracts more than in its separate state, and the other less, the electric fluid diffuses itself amongst them in quantities proportionate to their relative attractions, and they consequently appear unelectrified. But if they are suddenly separated, the new distribution of the electric fluid remains whilst the original attractions are restored; and as these are not equal to each other, the bodies will appear electrical: that whose natural attraction was increased by contact, having received an addition to its quantity of electric fluid, will be positively electrified; and that whose attraction was lessened, having lost a portion, will be negative."

"Take as an instance the electrical machine: let the attraction of the cushion for the electric fluid be represented by 20, and that of a similar surface of glass by 30: the sum is 50. Bring the bodies in contact, their attractions alter; that of the glass becomes 40, and that of the cushion 10; the sum of these is still 50: the natural electricity, therefore, though unequally distributed, is still equal to the sum of its attractions, and does not appear, for the cause of its unequal distribution (the contact) is still active. Separate the glass from the cushion, its original attraction of 30 will now only operate, but it has acquired 40 of electricity by contact with the cushion; the glass is therefore positive with force equal to 10. The cushion will now also have its original attraction of 20; but its electricity amounts only to 10. It is therefore negative with a force equal to 10. And here is seen the reason why positive and negative bodies act more powerfully on each other than on indifferent matter, for their mutual difference is often twice as great as their individual, since if the latter be 10, the former may be 20.

"The effects now described continually recur during the revolutions of the cylinder, every part of which is successively brought in contact with the cushion, and passes forward with the electricity it thus progressively acquires. The silk flap may be considered as a continuation of the rubber, which, by partially maintaining the altered attraction of the glass, counteracts the tendency of the acquired electricity to pass back into the cushion. The surface of the glass, when it passes from beneath the silk flap, has not this compensation. Hence the acquired electricity is there uncombined, and has a tendency to diffuse itself among the surrounding bodies: the conductor, with its row of points, is the nearest reservoir, and into this it passes, and the conductor becomes thereby *positively electrified.* During this process the cushion and its attached conductor constantly furnish electricity to the glass, and *they* are consequently negative in the same degree; but they have only a *limited* surface and a *certain quantity* of natural electricity, and if perfectly *insulated* can furnish only a definite portion; but if they are connected with the ground whose surface is comparatively *unlimited,* they operate upon an extensive store, to the supply of which there appears no assignable bound. It is for this reason that the electricity of either conductor *separately* is more apparent when the opposite one is insulated." *

Such is the view of the theory of a single fluid modified, as it has been since it was first proposed by its illustrious author, to adapt it to the phenomena of the science in its modern state. Different partisans of this theory accept it with different qualifications and conditions; but the above may be considered in the main as a fair statement of the hypothesis by a recent electrician who advocated its validity.

Considering what was observed respecting physical theories in general at the commencement of this chapter, it is needless to state that a theory which has been so long and so extensively accepted as the true one, is quite sufficient to afford an explanation of all the ordinary phenomena of electricity. It is not, therefore, by such means that the question can be decided between these two celebrated theories. That question can only be settled by requiring from each of them an account of some phenomena which have more recently attracted the attention of electricians, but above all by demanding from each of them a rigorous numerical estimate of the state of bodies brought under each other's influence in an electrified state in cases which we shall presently explain.

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* Singer's Electricity.

Meanwhile it may be right here to give the particular details of some striking and beautiful experiments, which are much relied on by the advocates for the theory of a single fluid, as being decisive tests in favour of the reality of that theory.

Experiment I.

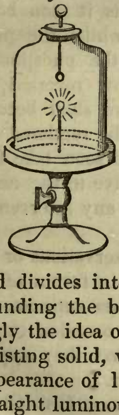
(148.) To the conductor of a machine so arranged as to be charged with negative electricity present a pointed metal rod held in the hand, in a darkened room. A cone, formed of rays of light, will be seen, having its vertex at the point and its base towards the conductor; but if a similar point be presented to a positively electrified body, instead of the cone of light there will be seen a brilliant star at the extremity of the metallic point. The light in these experiments is considered to indicate the course of the electric fluid. The point is a sort of pipe capable of emitting or receiving it. The negative conductor is supposed to have a deficiency, and the point presented towards it is illuminated by a diverging pencil of rays, which indicates that the cause of that light moves from the point to the negative body. The positive conductor is supposed to have an excess of electric fluid, and the point presented to it is merely illuminated by a globular spot of light, an appearance that may be conceived to attend the entrance of a subtle fluid into it.

Reversing the experiment, by connecting the points with the conductors respectively, the converse series of phenomena is produced.

Experiment II.

(149.) Take the transfer plate of an air-pump, and affix to its centre, by a wire three inches long, a brass ball one inch in diameter (*fig.* 30.); connect a similar ball, by a sliding wire, to the top of a receiver, and place this over the transfer plate, so that the one ball may be vertically over the other, and at the distance of about one inch. Exhaust the receiver accurately, and then connect the plate with the negative conductor, and the upper wire and ball will be positive. Upon turning the machine, a torrent of beautiful light will pass from the positive to the negative ball, on which it breaks and divides into a luminous atmosphere, entirely surrounding the ball and stem, and conveying most strikingly the idea of a fluid running over the surface of a resisting solid, which it cannot enter with facility. No appearance of light occurs on the positive ball, but the straight luminous line that passes from it; but if it be rendered negative and the lower ball positive, these effects are entirely reversed.

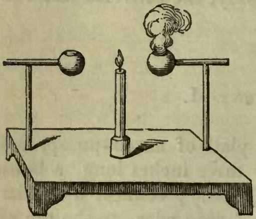
Fig. 30.



Experiment III.

(150.) *Fig.* 31. represents two hollow metal balls, about $\frac{3}{4}$ of an inch in diameter, insulated upon separate glass pillars, by which they are supported two inches apart; the upper part of each ball is indented, so as to form a small cup, in which a fragment of phosphorus is to be placed. A small candle or lamp has its flame situated midway between the balls; one of them is connected with the positive, the other with the negative conductor of the electrical machine by means of a wire. When the balls are electrified the flame is agitated, and inclines to that which is negative. This it soon heats sufficiently to fire the phosphorus, whilst the positive ball remains perfectly cold, and the phosphorus solid. If the connecting wires be now reversed, so that the ball which was before negative shall become positive, and that which was positive be rendered negative, the phosphorus in the latter will soon take fire. So that electricity passes from the positive to the negative, and transmits with it the heat of any intervening ignited body.

Fig. 31.



We shall not now enter into any observations or argument drawn from these experiments, in favour of the theory of a single fluid. There are other experiments, of the same kind, which we shall have occasion to explain hereafter, when it will appear that they may be accounted for in a very different manner.

(151.) About the year 1760, Æpinus, Int. (82.), brought the Franklinian theory to the test of strict mathematical statement, and obtained numerous results in general accordance with the phenomena. He found, however, that the mere hypothesis of an elastic fluid, whose molecules attracted and were attracted by the particles of bodies, even admitting this attraction to vary in different bodies, and in different states of the same body, was insufficient to explain the phenomena, and that to bring the theory into accordance with the facts, a further assumption must be made, that masses of matter exercise upon each other, at great distances, a reciprocally repulsive force of sensible amount, similar to the repulsion which exists among the molecules of the electric fluid itself.

If no other reason could be assigned for rejecting the theory of a single fluid as untenable, than this assumption of a mutual repulsion, of the existence of which there is not only no evidence whatever, but which is in immediate opposition to all the laws developed by the motions of the great bodies of the universe, we should be justified in its rejection. The illustrious proposer of this theory did not himself see the necessity for so unphilosophical an assumption. In the loose manner in which the theory was in his time applied, it was sufficient to explain in a general manner the limited body of phenomena then observed; and it was not until further observation and inquiry had multiplied the facts, and a more rigorous account of those facts was exacted, and it became necessary to reduce the theory to a strict mathematical form, that the necessity of this additional assumption of a repulsion between matter and matter at a distance, so completely opposed to the most striking phenomena in nature, became apparent.

But supposing this hypothesis, objectionable as it is, to be admitted, would the theory even then be sufficient for the due explication of the phenomena? That it would afford a reasonable explanation of the ordinary attractions and repulsions, and the chief electrical effects upon bodies by induction, may be admitted; for no theory which could fail in giving a reasonable account of effects so conspicuous, could have obtained any acceptance. It does not appear, however, in what way a theory, in which different kinds of matter must be admitted to exert different attractions for the electric fluid, can explain the distribution of electricity on the surfaces of conducting bodies, in a manner depending *solely on their form*, and not at all on their *chemical composition*. If different material substances have different attractions for the electric fluid, how does it happen that the distribution of that fluid on an oblong plate of metal, of given dimensions, will be the same, of whatever metal the plate be formed, or even though it be formed of pieces of various different metals connected together? Neither can that theory show why negative electricity, which it views as a deficiency or absence of the electric fluid, should, when developed on the surfaces of bodies, produce effects in conformity with the rigorous hydrostatical laws, which an elastic fluid would obey, whose molecules repel each other with forces which diminish in intensity as the square of the distance between them increases. If this theory of a single fluid fail in affording a reasonable explanation of such striking phenomena, its insufficiency becomes still more glaring when by its principles an attempt is made to calculate the depth of the electric fluid on bodies of various forms, brought under each other's influence in given positions. Thus, if two spheres composed of a conducting substance are brought into contact and electrified, and then separated, it will be found, that round the point of contact, on the smaller sphere, electricity will be diffused of a kind contrary to that with which the spheres were electrified; and this electricity will extend to a certain distance round the point of contact, beyond which the electricity diffused over the remainder of the sphere will be the same as that with which the two spheres were electrified. The theory of a single fluid cannot account for this general fact; still less can it enable us to compute the limits which separate the portions of the sphere electrified by the one electricity from that electrified by the other. On the other hand, the hypothesis of two fluids, observing the conditions by which that hypothesis is restricted, not only enables us to show that under these circumstances the development of a contrary electricity round the point of contact, and of the same electricity over the remainder of the sphere, is a natural and inevitable consequence of the properties, which, in this theory, are assigned to the two fluids, but it enables us to calculate with the most surprising precision the exact limits which, in any given position, separate the positive from the negative regions of the smaller sphere.

The mathematical problems involved in the application of the theory of two fluids to the explanation of electrical phenomena require for their solution the last resources of the most profound analytical researches of modern science. It would not be consistent with the object of a treatise like the present to enter into the details of such investigations. The language itself, in which alone the general theorems of electricity must be expressed, would be unintelligible to the great majority of our readers. Much may be done to popularise mathematics, and more especially those parts of mathematics which express the laws of physical phenomena; but this advantage has practical limits beyond which it cannot be carried, and in the whole range of mathematical physics it would probably be difficult to find a portion of science which would more decidedly forbid any attempt at popular or elementary exposition than the results of the mathematical investigation of electrical phenomena. Although we cannot pretend, therefore, to deliver here even an abridged view of the splendid labours of Poisson in this department of physics, we shall endeavour to select a few results at which he has arrived; and by showing their accordance with the phenomena, we may direct and encourage those who have time and opportunity to pursue experimental inquiry to those points which analysis has suggested, and thereby enable them to supply new facts which will either fulfil the predictions of theory, or show by their departure from these anticipations in what respects theory must be modified in order more perfectly to represent the phenomena.

(152.) The first proposition which presents itself for solution is to determine the distribution of the electric fluid upon an insulated conductor of a given form which is charged with electricity of any given intensity. The analytical conditions immediately derivable from the hypothetical properties of the electric fluid ought to solve this problem. If we view the electric fluid as being of uniform density in every part, a supposition which is suggested by the self-expansive property of that fluid, we must regard its varying intensity at different parts of the surface of the electrified conductor, or what we have occasionally called its varying *density,* to be the consequence of the varying depth of the fluid on different parts of the surface. But as the atmospheric pressure keeps the superior surface of the electric fluid level with the surface of the body itself, the problem proposed will resolve itself to the determination of the inferior surface, or to the law according to which the depth of the electric fluid varies on different parts of the conductor. If it be more consonant with the notions of some persons to view the electric fluid as being of uniform depth, and to ascribe the varying intensity which is found by experiment to prevail at different parts of the same electrified conductor to a variation in the density of the electric fluid, such a supposition may be equally entertained, and the calculations will remain undisturbed, save that the numbers which in the one case indicate the *depths* of electric fluid in the other case express its *densities.*

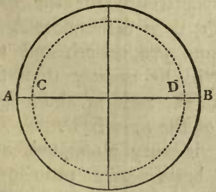
Supposing, then, that the electric fluid were diffused upon an insulated electrified conductor, the analytical conditions by which its state is expressed will be those by which the conditions of equilibrium are declared to subsist between the attractions and repulsions exercised by the various molecules of the electric fluid diffused over the conductor on the natural electricities of each particle of matter in the conductor. It is evident that this is a condition, and the only condition, of electrical equilibrium. If the combined attractions and repulsions of the electric fluid diffused over the conductor, acting on the natural electricities of any one or more of its particles, were not in equilibrium, the resultant of such forces would produce a decomposition of the natural electricities of such particle or particles, and an evolution of electricity would be the consequence, which would contradict the supposition of electrical equilibrium assumed as the basis of the hypothesis. The analytical formulæ by which such conditions are expressed must depend on and be derivable from the laws of attraction and repulsion, assumed in the electrical theory conjointly with the form of the conductor.

The exterior surface of the electric fluid diffused over the conductor being assumed to be identical with the surface of the conductor itself, these analytical conditions will necessarily supply the means of obtaining its interior surface.

The problems arising from the application of such principles to particular forms of conductors offer mathematical difficulties of the most formidable kind, and in many cases their complete solution cannot in the present state of mathematical science be effected. The form of the conductors in some cases, however, renders the solution comparatively simple.

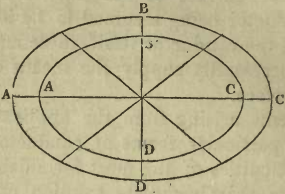
(153.) It has been demonstrated by Newton that a spherical shell of uniform thickness surrounding a sphere composed of matter whose attraction increases as the square of the distance is diminished, exercises forces on any point within the sphere which are in mechanical equilibrium. This is the most simple case of the preceding problem, and it follows from it that the diffusion of the electric fluid on the surface of a sphere of conducting matter is uniform. Thus if A B (*fig.* 32.) represent the section of a sphere of conducting matter made by a plane through its centre, the concentric circle C D will represent the inferior surface of a stratum of electric fluid diffused upon it.

Fig. 32.



If an elliptical speroid be surrounded by a shell of attracting matter governed by the same law of the inverse square of the distances, the form which would reduce its attractions on any particle within the spheroid to equilibrium would be one bounded by similar elliptical surfaces. If the section of such a spheroid, therefore, be represented by A B C D (*fig.* 33.), the

Fig. 33.

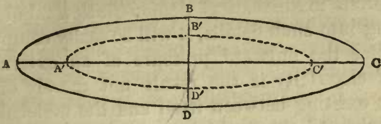


section of the interior surface of the electric shell will be represented by A′ B′ C′ D′, being an ellipse having the same centre and axes, and similar to it; that is to say, one whose axes are in the same proportion.

Since the distance between the surfaces of two such ellipsoids at their vertices is the difference between their semiaxes, it follows that the depths of the electricity at the vertices of an ellipsoid formed of a conducting substance are proportional to the axes terminated at these vertices respectively; for the axes being proportional to each other, their differences A A′ and B B′ will be in the same proportion, and the depth of the electricity at A will be greater than the depth of the electricity at B in the ratio of the length of the axis A C to the length of the axis B D.

(154.) When an ellipsoid is very elongated, and therefore its longitudinal axis bears a great ratio to its lesser axis, the depth of the electricity will be proportionably greater at its ends. For example, if we suppose a spheroid to be formed by the revolution of a very elongated ellipse, such as A B C D (*fig.* 34.), on its major axis A C, the thickness of the electric fluid will

Fig. 34.



be greater at the ends A and C of its longer axis than round its equator, formed by the revolution of the points B and D in the proportion of A C to B D.

(155.) Since any part of a body which has a gradually tapering form, and is terminated in a point, may be considered to be part of an extremely elongated elliptical spheroid, the point being one of the extremities of its longer axis, the principle here established will show that the depth of the electricity at such a point would be very great, if it could be maintained there; but in all such cases, when the electricity has a sensible force on other parts of the conductor, its intensity at the point will greatly exceed the atmospheric pressure, and it will escape from the point into the air, as it is found by experience to do.

(156.) It would be easy to verify, in a general manner, these conclusions by constructing elliptical spheroids of metal, and electrifying them. On examining with the proof plane and the electrometer the densities of the electricity at their vertices, the accordance of the results with the theory will be apparent; but we shall presently state results of experiments made by Coulomb, which will afford other satisfactory proofs of such accordance.

(157.) The tendency of the electricity diffused upon a body to overcome the atmospheric pressure increases not merely in the proportion of the simple ratio of the depth of the electricity, but is proportional to the *square* of that depth. Thus, if the depth of the electricity in the neighbourhood of an angular or pointed part of a conductor be ten times greater than its depth at another part of the surface, the pressure of the electricity against the air will be a hundred times greater. This admits of rigorous mathematical demonstration; but, without entering into such details, it will be easily comprehended that since the outward pressure of an external molecule of electricity is the result not merely of the repulsion existing between itself and the molecules under it, but also of the repulsion existing between each of those molecules and those below it, the combined effects of all the repulsions will be as the square of the depth. Due consideration of these properties will explain the great facility with which even feeble charges of electricity are dissipated at the angular points and edges of bodies, and why conductors, which are intended to retain upon them the electricity with which they are charged, are every where made in a rounded form.

(158.) Having established the general analytical conditions under which electricity is maintained in equilibrium on a single conducting body, Poisson next applied himself to the solution of the more difficult and complicated problem,— to determine the distribution of electricity on two or more conductors, either brought into actual contact, or so placed as to be affected by their mutual electricities. The difficulties which this general problem presented were happily surmounted by showing that whatever might be the number or form of electrified bodies brought under each other's influence, the electricity diffused upon them when in a state of equilibrium must be subject to a single general condition, which has the double advantage of being self-evident, and of being immediately expressed in mathematical language. The following is this condition as announced by Poisson.

(159.) *If two or more electrified conductors are brought near each other, and the electric fluid upon them has acquired a state of equilibrium, it will be necessary that the resultant of the actions of all the molecules of electric fluid diffused upon them, exerted upon any point whatever assumed within the dimensions of any one of these bodies, be nothing. For if this resultant were not* *nothing, the natural electricities of the point on which these forces would act would be decomposed, an evolution of electricity would take place, and the electric state of the body would be changed, contrary to the supposition which has been made of its equilibrium.*

This principle, when reduced to mathematical expression, supplies all the equations or conditions necessary to determine the distribution of electricity on each of the bodies; and if analytical science were sufficiently advanced to supply the means of solving these equations in every case, the phenomena of electrified bodies could be as accurately calculated and as certainly foreseen as the movements of the bodies of the solar system. In most cases, the complete resolution of these equations surpasses the power of analysis. Poisson has, however, succeeded in surmounting the analytical difficulties which they present in certain particular cases, in which the electrical state of bodies had been long before experimentally examined by Coulomb. The comparison of the numerical results of the theoretical calculations effected by Poisson, in those particular cases, with experiments made before the theory which supplies these results had been propounded, has afforded conclusive proofs of the soundness and truth of that theory, and furnishes one of the most beautiful examples to be found in the history of physical discovery of the cooperation of experimental and theoretical inquiry in the discovery of a great natural law. The bodies on which Coulomb had experimented, and whose electrical state he had minutely examined and recorded, were *spheres;* and Poisson succeeded in rendering the general analytical conditions capable of solution when applied to the particular case of two spheres charged with given quantities of electricity, and brought either into actual contact or near each other.

(160.) According to the theory of Poisson, when a body is in its natural state it contains equal quantities of positive and negative electricity. Each of the two fluids will be uniformly diffused through its dimensions;

and as one of them attracts whatever the other repels, and these attractions and repulsions are equal, the mechanical forces thus exerted by the two fluids will be in equilibrium. Hence, if two spheres be in their natural state, their effect on each other will be nothing; and if they are not submitted to the influence of some third body, they will continue in the natural state. But if, besides the natural charge of electricity of the two kinds, an excess of either electric fluid, as, for example, the positive, be imparted to either sphere, it will diffuse itself over the surface, forming a thin stratum upon it of uniform depth. The attractions of this stratum on any particle within the sphere on which it is diffused are in equilibrium, and therefore it cannot, of itself, liberate or decompose the combined electricities of any particle of that sphere; but this is not necessarily the case with respect to the particles of the other sphere. On the contrary, by attracting the negative part of the combined electricities, and repelling the positive, it will in general effect a partial decomposition of them; and the fluids thus liberated will move to the surface, where they will be retained in a thin stratum by the atmospheric pressure. The depth of this stratum will vary in different parts of the sphere, according to a law which can be deduced from the theory.

(161.) The fluids thus decomposed and liberated on the second sphere will react as well on the natural electricities of the first sphere as on the excess of the positive electricity with which it was charged, and a new distribution of electricity on that sphere would be the consequence. When the mutual decompositions produced by these actions are completed, the electric fluids which are free will dispose themselves in a certain manner on the two spheres, and the depth and the quality of the fluid at each point of each of the spheres can be determined by theory, when the radii of the spheres and their mutual position with respect to each other are given. It may, however, be observed in general, that the reciprocal action of the two spheres can, in no case, increase or diminish the difference between the quantities of positive and negative fluids upon them. This difference must always be equal to the excess of positive or negative fluid which has been originally imparted to them by any third body or bodies by which either or both of them may have been electrified; for since their natural electricities contain equal quantities of the positive and negative fluids, any decomposition which has been effected by their mutual action must develop equal quantities of the positive and negative fluids. Such action, therefore, always adding equal quantities to the positive and the negative fluids with which the spheres are already charged, leaves their difference unaltered.

(162.) If two conducting spheres, differently charged with electricity, be brought into contact, the fluids will distribute themselves between them, in a certain proportion depending on the radii of the spheres. If, before the contact, the electricities with which they are charged happen to be in this proportion, no electricity will pass from either to the other when brought into contact; but if the electricities with which they are charged before contact be in any other proportion than when contact takes place, it will distribute itself in the proportion due to the relative magnitude of the spheres.

When the spheres have been separated after contact, the total quantities of electricities upon them, estimating these quantities by the excess of the positive above the negative, or, *vice versâ*, will be the same as when in contact; but its distribution over their surfaces will be different, being affected by the varying distance between their centres.

(163.) We propose here to state some of the results of the mathematical investigations of Poisson, and to compare them with the results of the experiments of Coulomb; and, for the sake of clearness, we shall resolve the theorems which are to be explained into a series of distinct propositions. We shall *first* consider the cases in which the spheres are brought into contact; *secondly*, when after contact they are separated, no additional electricity being imparted to them after contact; and, *thirdly*, the cases in which the two spheres are charged with any quantities of electricity, and brought under each other's influence without previous contact.

PROPOSITION I.

(164.) *Two conducting spheres of given radii are charged with electricity and brought into contact: it is required to determine the proportion in which the sum of their electrical charges will be shared between them when electrical equilibrium has been established after contact, and also the mean depth of electricity on each sphere.*

Let r and r' be the radii of the spheres.

Let E and E′ be the quantities of electricity which each will have after contact.

Let D and D′ be the mean depths on each after contact.

From what has been explained in (93.) we have

$$E = 4\pi r^2 D, \quad E' = 4\pi r'^2 D'.$$

$$\therefore \frac{E'}{E} = \frac{r'^2 D'}{r^2 D} \dots [1]; \text{ or } \frac{D'}{D} = \frac{E'}{E} \cdot \frac{r^2}{r'^2} \dots [2.]$$

By the formula established by Poisson we have

$$E - E' = -4\pi^2 mhr \cot. (1-m)\pi;$$

$$E = 4\pi rmh \int \frac{t^{m-1}-1}{1-t} dt;$$

$$\frac{D'}{D} = \frac{r^2 . E'}{r'^2 . E} = \frac{r^2}{r'^2} \left\{ 1 - \frac{E-E'}{E} \right\};$$

$$\therefore \frac{D'}{D} = \frac{r^2}{r'^2} \left\{ 1 + \frac{\pi \cot. (1-m)\pi}{\int \frac{t^{m-1}-1}{1-t} . dt} \right\} \dots [3.];$$

$$\therefore \frac{\mathrm{E}'}{\mathrm{E}}=1+\frac{\pi \cot.(1-m)\pi}{\int \frac{t^{m-1}-1}{1-t}.\,dt} \ldots .[4.];$$

where h is a constant quantity depending on the absolute amount of the electric charge, and $m=\frac{r'}{r+r'}$, and the integral is taken from $t=0$ to $t=1$.

When the values of r and r' are given in any particular case, the integral may be obtained by the usual methods of integration, and the value of $\frac{\mathrm{E}'}{\mathrm{E}}$ may be inferred, and this being known $\frac{\mathrm{D}'}{\mathrm{D}}$ may be computed.

(165.) Among the numerous experiments made by Coulomb, are several in which, after bringing into contact two electrified spheres, and separating them, he examined their state by means of his electrometer, and ascertained the depths of electricity upon them, and the relation between the amount of their total charges. By applying the formula [3.] obtained in Proposition I. to these particular cases, and comparing the quantities and depths of electricity thus derived from the formula with the actual quantities and depths given by the experiments, the theory from which the formula has been derived may be tested.

The experiments of Coulomb, to which we now refer, were conducted in the following manner: — One of the two spheres was first electrified by being applied to the prime conductor of an electrical machine, or by any other means. It was then introduced into the electrometer in the place of the fixed ball, the moveable ball having been previously charged with similar electricity. The moveable ball being repelled by it, was brought back to a certain distance from it, suppose, for example, 30°, by turning the micrometer of torsion, and the angle of torsion necessary to keep the moveable ball at this distance was observed.

The electrified sphere was now withdrawn from the electrometer, and brought into contact with the other sphere. By this means the charge of electricity originally given to the former sphere was shared between the two. The spheres being again separated, the sphere first electrified was again placed in the electrometer. Having lost a part of its charge of electricity, it now exerted a less repulsion than before on the moveable ball; and on bringing the latter to stand at the same distance of 30° from it, a less angle of torsion was necessary. The difference between the first angle of torsion and the second must represent the electricity lost by the contact, and must therefore represent the electricity imparted to the other sphere. Let this difference be A′; and let A express the angle of torsion which kept the sphere at 30° from the moveable ball after the contact. Also let E and E′ express the quantities of electricity on the spheres respectively after the contact. It is evident then that we shall have

$$\frac{E'}{E}=\frac{A'}{A}\dots\text{[5.]}$$

Having thus ascertained the ratio of the whole quantities of electricity on the two spheres, their relative depths would be given by the formula [2.], the radii being known.

In the interval which elapsed between the first introduction of the electrified sphere into the electrometer and its second trial after the contact, a loss of electricity must have taken place both on the sphere and on the moveable ball of the electrometer by contact of the air, which would affect the result of the experiment. This loss, however, was ascertained upon the principles explained in Chap. IV., and the necessary correction was made in the angles of torsion. The angles A and A′

may therefore be considered as free from any error due to atmospheric dissipation.

(166.) In some cases this method cannot be conveniently practised. If the magnitude of the greater of the two spheres be too considerable to allow of its being introduced into the electrometer, it would be necessary to electrify in the first instance the smaller sphere; but if in that case the spheres be very unequal in magnitude, the latter would undergo too great a change in its charge of electricity by contact with the greater. In such cases Coulomb proceeded in the following manner: — The greater sphere C was first electrified, and being insulated, the smaller sphere C′ was placed in contact with it, by which this latter became charged with electricity. The lesser sphere C′ was then placed in the electrometer, and the angle of torsion necessary to retain the moveable ball at a given distance from it was observed. Suppose this angle to be A_1. The sphere C′ being then withdrawn from the electrometer, was deprived of its electricity by being touched by the hand. It was then again brought into contact with the greater sphere C, and being withdrawn its electricity was again discharged by touching it. This was repeated a certain number of times, the electricity acquired by C′ at each contact with C being always discharged before the next contact. After the last contact, the sphere C′ was again placed in the electrometer, and the angle of torsion necessary to retain the moveable ball at the same distance from it was observed. Suppose this angle to be A_n. The proportion in which the electricity was shared between the two spheres was inferred from A_1 and A_n, on the following principles.

Whatever be the quantity of electricity with which C may be charged, it will be shared with C′ by contact in the same proportion.

If then E and E′ be the quantities with which the spheres are charged after the first contact, and if $E = zE'$, then z will express the ratio of the quantities of electricity with which the spheres are charged after any succeeding contact. By the second contact the quantity E, with which the first is charged, is therefore shared between the two spheres in the proportion of z to 1. The charge of the sphere C will then be $\mathrm{E}\dfrac{z}{1+z}$, and that of the sphere C′ will be $\mathrm{E}\dfrac{1}{1+z}$. After the third contact, the quantity of electricity $\mathrm{E}\,.\,\dfrac{z}{1+z}$ will be as before, shared between them in the same ratio of z to 1. Therefore the charge of C will be $\mathrm{E}\,.\,\dfrac{z^2}{(1+z)^2}$, and that of C′ will be $\mathrm{E}\,.\,\dfrac{z}{(1+z)^2}$. In like manner, after the n^{th} contact, the charge of C will be $\mathrm{E}\,.\,\dfrac{z^{n-1}}{(1+z)^{n-1}}$, and that of C′ will be $\mathrm{E}\,.\,\dfrac{z^{n-2}}{(1+z)^{n-1}}$.

But since the repulsion of C′ after the first contact was balanced by the torsion A_1, and after the n^{th} contact by the torsion A_n, we shall have

$$\frac{\mathrm{E}}{z} : \mathrm{E}\,.\,\frac{z^{n-2}}{(1+z)^{n-1}} :: \mathrm{A}_1 : \mathrm{A}_n\,;$$

$$\therefore \frac{z^{n-1}}{(1+z)^{n-1}}=\frac{\mathrm{A}_n}{\mathrm{A}_1}.$$

Let $\dfrac{z}{1+z}=y$, and take the logarithms, and we obtain

$$(n-1)\log. y=\log. \mathrm{A}_n-\log. \mathrm{A}_1\,;$$

$$\therefore \log. y=\frac{\log. \mathrm{A}_n-\log. \mathrm{A}_1}{n-1}.$$

Hence, when A_n and A_1 are known by observation, y

may be found, from which z may be derived, and therefore the ratio of the electricities $\frac{E'}{E}$ will be known.

In the practice of this latter method of experimenting, it is especially necessary to take into account the loss of electricity by the contact of the air, and even the loss by imperfect insulators; for so considerable a time must elapse between the moments at which the lesser sphere is placed in the electrometer, that these losses must be expected to be of sensible amount. In an experiment made by Coulomb by this method he touched the greater sphere C twenty times with the lesser sphere C′, and found it necessary to allow for a loss of one eighth part of the whole electricity by the contact of the air in the interval. It does not appear that he made any correction for imperfect insulation; and this, as we shall see hereafter, exposed this experiment to more extensive limits of error.

(167.) Coulomb's experiments to determine the proportion in which electricity is shared between two spheres brought into contact were made with spheres whose diameters were in the ratio of 2 to 1, 4 to 1, and 8 to 1. In the first two cases he proceeded by the method explained in (165.), but in the last case he adopted the method described in (166.). The results of these experiments are given in the following table, where the radius of the lesser sphere is supposed $=1$, and the quantity of electricity on the greater sphere also $=1$. The depths are obtained by the formula [2.], Proposition I., the depth on the greater being $=1$.

Radius of greater sphere.	Quantity on lesser sphere.	Depth on lesser sphere.
2	0·27	1·08
4	0·0909	1·33
8	0·02566	1·64

To compare these experimental quantities with those deducible from the theory, it is only necessary to make the necessary substitutions in the formulæ [2.] and [3.], and execute the calculations.

1. In [4.], Proposition I., let $r=2$, $r'=1$; $\therefore$ $m=\frac{1}{3}$; and the integral in the denominator becomes

$$\int \frac{t^{-\frac{2}{3}}-1}{1-t} dt$$

Let $t=\theta^3$, and therefore $t^{-\frac{2}{3}}=\frac{1}{\theta^2}$. Hence the integral is transformed into

$$3 \cdot \int \frac{\theta^{-2}-1}{1-\theta^3} \cdot \theta^2 d\theta = 3 \cdot \int \frac{1-\theta^2}{1-\theta^3} d\theta.$$

This being integrated between the limits $\theta=0$ and $\theta=1$, gives

$$\frac{E'}{E}=0\cdot 29, \quad \frac{D'}{D}=1\cdot 1601$$

2. In [3.] let $r=4$, $r'=1$, $\therefore m=\frac{1}{5}$. If, as above, we put $t=\theta^5$ and proceed as before, we shall obtain

$$\frac{E'}{E}=0\cdot 0823, \quad \frac{D'}{D}=1\cdot 3168.$$

3. In [4.] let $r=8$, $r'=1$, $\therefore m=\frac{1}{9}$; and if we put $t=\theta^9$, we shall obtain

$$\frac{E'}{E}=0\cdot 0226, \quad \frac{D'}{D}=1\cdot 4443.$$

Placing then these results of theory in juxtaposition with the corresponding quantities obtained by experiment, the comparison is exhibited in the following table · —

Radius of greater sphere.	Quantity of electricity on lesser sphere.		Depth of electricity on lesser sphere.		Ratio of the observed to the computed quantities.
	Theory.	Observation.	Theory.	Observation.	
2	0·29	0·27	1·1601	1·08	0·93
4	0·0823	0·0909	1·3168	1·33	1·01
8	0·0226	0·02566	1·4443	1·64	1·14
Mean ratio of the observed to the computed values - - - - - - -					1·03

In the first two cases the coincidence of theory and experiment is evidently within the limits of the errors of observation, and the greater discrepancy which appears in the last case is satisfactorily accounted for by the nature of the experiment, as already explained (166.)

PROPOSITION II.

(168.) *When two electrified spheres are brought into contact, and then separated, the electric fluid is spread with a greater depth on the lesser than on the greater sphere; taking the depth* (D) *on the greater as the unit, it is required to find the limiting value of the depth* (D′) *on the less when its radius* r' *is indefinitely diminished.*

By making certain transformations on the formula for $\frac{D'}{D}$, Poisson has shown that when $\frac{r'}{r+r'}=0$, it will become

$$\frac{D'}{D}=\int\frac{\log.\frac{1}{t}}{1-t}\,dt=\int\log.\frac{1}{t}\left\{1+t+t^2+t^3\ldots\right\}dt;$$

$$\therefore\ \frac{D'}{D}=1+\frac{1}{2^2}+\frac{1}{3^2}+\frac{1}{4^2}+\ldots\ldots$$

$$\frac{D'}{D}=\frac{\pi^2}{6}=1{\cdot}6449.$$

This is a result which, from its nature, cannot be verified directly by experiment. By gradually increasing the ratio of the greater to the lesser sphere, Coulomb conjectured that the limit of the ratio of the depths might be about two to one, being about one fifth more than the value given by theory.

The result of the experiment with two spheres whose diameters are as eight to one, shows that beyond that proportion the relative depths on the smaller sphere will acquire no sensible increase.

PROPOSITION III.

(169.) *Two electrified conducting spheres are maintained in contact: it is required to determine the depth of the electric fluid at the points diametrically opposite the point of contact.*

Let X and X′ be those depths, and let the former symbols retain their significations. By Poisson's formula we have

$$\mathrm{X}=\frac{m^2h}{4r}\cdot\int\frac{t^{\frac{m}{2}-1}-t^{-\frac{m}{2}}}{1-t}\cdot\log.\frac{1}{t}\cdot dt\ \ldots\ldots [6.]$$

$$\mathrm{X}'=\frac{(1-m)^2h}{4r'}\cdot\int\frac{t^{-\frac{m+1}{2}}-t^{\frac{m-}{2}}}{1-t}\cdot\log.\frac{1}{t}.dt\ \ldots [7.]$$

PROPOSITION IV.

(170.) *Two equal electrified spheres are maintained in contact; to find the depth of the electricity at the points diametrically opposite the point of contact.*

In this case $r=r'$; $\therefore\ m=\frac{1}{2}$, which renders $\mathrm{X}=\mathrm{X}'$.

And we have

$$X = \frac{h}{16r} \cdot \int \frac{t^{-\frac{3}{4}} - t^{-\frac{1}{4}}}{1-t} \cdot \log. \frac{1}{t}\, dt.$$

To prepare this for integration let $t = \theta^4$, and we find

$$X = \frac{h}{r} \cdot \int \frac{1-\theta^2}{1-\theta^4} \cdot \log. \frac{1}{\theta} \cdot d\theta = \frac{h}{r} \cdot \int \frac{1}{1+\theta^2} \cdot \log. \frac{1}{\theta} \cdot d\theta.$$

Expanding $\frac{1}{1+\theta^2}$ this becomes,

$$X = \frac{h}{r} \cdot \int \{1 - \theta^2 + \theta^4 - \theta^6 + \ldots\} \log. \frac{1}{\theta} \cdot d\theta.$$

But between the limits

$$\theta = 0 \text{ and } \theta = 1 \,.\int \theta^n \cdot \log. \frac{1}{\theta} \cdot d\theta = \frac{1}{(n+1)^2};$$

$$X = \frac{h}{r} \left\{ \frac{1}{1^2} - \frac{1}{3^2} + \frac{1}{5^2} - \ldots \right\}$$

By taking a sufficient number of terms for the necessary approximation, we find

$$X = 0{\cdot}916 \frac{h}{r}.$$

To find in the same case the mean depth of the fluid D, we have, by Proposition I.,

$$D = \frac{E}{4\pi r^2} = \frac{mh}{r} \cdot \int \frac{t^{m-1} - 1}{1-t} \cdot dt \ldots . [8].$$

But in this case $m = \frac{1}{2}$. Hence

$$D = \frac{h}{2r} \cdot \int \frac{t^{-\frac{1}{2}} - 1}{1-t} \cdot dt = \frac{h}{r} \cdot \int \frac{d(t^{\frac{1}{2}})}{1 + (t^{\frac{1}{2}})} = \frac{h}{r} \log. 2.$$

Hence we shall have $D = 0{\cdot}693 \cdot \frac{h}{r}$ for the mean depth.

Hence the ratio of the depth at the point most remote from the point of contact to the mean depth is

$$\frac{\mathrm{X}}{\mathrm{D}}=\frac{0{\cdot}916}{0{\cdot}693}=1{\cdot}322.$$

(171.) Coulomb brought several pairs of unequal spheres into contact, and ascertained by the proof plane and the electrometer the ratio of the depth of the electricity on the smaller sphere at the point most remote from the point of contact with the mean density on the greater sphere. In order to compare his observations with the theoretical values of this ratio, we shall investigate the particular case of the general formula, which will include these experiments.

Proposition V.

(172.) *To calculate the ratio of the depth of the electric fluid on the point of the lesser of two electrified spheres in contact most remote from the point of contact to the mean depth on the greater sphere, in the cases in which the radii of the spheres are in the ratios* 1 : 2, 1 : 4, *and* 1 : 8 *respectively.*

By [7.] and [8.] we find

$$\frac{\mathrm{X}'}{\mathrm{D}}=\frac{(1-m)^2 r}{4mr'}\cdot\frac{\displaystyle\int\frac{t^{-\frac{m+1}{2}}-t^{\frac{m-1}{2}}}{1-t}.\log.\frac{1}{t}.dt}{\displaystyle\int\frac{t^{m-1}-1}{1-t}.dt}$$

First. Let $r=2r'$, $\therefore m=\frac{1}{3}$. Let $t=\theta^3$, and the integrals in the numerator and denominator will become respectively

$$-9\int\frac{1-\theta}{1-\theta^3}\,.\,\log.\frac{1}{\theta}\,.\,d\theta\,;$$

$$3\int\frac{1-\theta^2}{1-\theta^3}\,.\,d\theta.$$

Each of which may be obtained by series; and taken between the limits $\theta=0$ and $\theta=1$, we shall find

$$\frac{X'}{D}=1{\cdot}834.$$

Secondly. Let $r=4r'$, $\therefore m=\frac{1}{5}$. In this case let $t=\theta^5$, and the integrals in the numerator and denominator become respectively

$$-25\int\frac{\theta-\theta^2}{1-\theta^5}\,.\,\log.\,\frac{1}{\theta}\,.\,d\theta\,;$$

$$5\int\frac{1-\theta^4}{1-\theta^5}\cdot d\theta\,;$$

which being integrated by series between the same limits, gives

$$\frac{X'}{D}=2{\cdot}477.$$

Thirdly. Let $r=8r'$. $\therefore m=\frac{1}{9}$. In this case let $t=\theta^9$, and the integrals in the numerator and denominator will become

$$-81\int\frac{\theta^3-\theta^4}{1-\theta^9}\,.\,\log.\,\frac{1}{\theta}\,.\,d\theta\,;$$

$$9\int\frac{1-\theta^8}{1-\theta^9}\,.\,d\theta\,;$$

which, as before, being integrated by series between the same limits, we find

$$\frac{X'}{D}=3\cdot087.$$

(173.) The results of Coulomb's experiments in these three cases, and of a similar experiment with equal spheres, are placed in juxtaposition with the three numbers determined here by theory and the number obtained for the case of equal spheres in the following table. In the fourth column the ratio of the computed to the observed numbers is given in each case. The radius of the lesser sphere is taken as the unit.

Radius of greater sphere.	Value of $\frac{X'}{D}$		Ratio of observed to computed value.
	By Theory.	By Observation.	
1	1·322	1·27	0·96
2	1·834	1·55	0·845
4	2·477	2·35	0·95
8	3·087	3·18	1·03
Mean ratio of the observed to the computed values - - - - - -			0·946

It appears, therefore, that the results of theory come within a twentieth part of those of observation.

(174.) Coulomb brought two equal electrified spheres into contact, and ascertained with the proof plane and the electrometer, that at the point of contact and in the space immediately around it, there was no sensible quantity of electricity on either sphere. He ascertained the depths at 30°, 60°, 90°, and 180°, from the point of contact, as compared with what the density would be if the spheres were removed from each other's influence, and the electric fluid allowed to diffuse itself uniformly upon them. In order to compare these results of observation with theory, we shall investigate the formula for this case.

PROPOSITION VI.

(175.) *Two equal electrified spheres are maintained in contact: it is required to determine the depth of electricity at any points upon them.*

Let φ be the angular distance of any point P on either of the spheres from their point of contact, and let π be the depth of the electricity at this point. By the formulæ established by Poisson, we have

$$x=\frac{h}{r}(A_0-A_1+A_2-A_3+\ldots.);$$

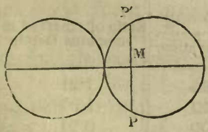
where

$$A_n=\frac{2n+1}{\{(n+1)^2-2(n+1)n\cos.\varphi+n^2\}^{\frac{3}{2}}}.$$

This series will be sufficiently convergent for calculation, except for those values of cos. φ which are nearly $=1$; and as these correspond to points near the point of contact, this is unimportant, since for such points it is known that the depth is insensible.

(176.) It is evident that for equal values of cos. φ, this will give equal values of x, and therefore that the depth of the electricity at equal distances from the point of contact is the same. In fact, if either sphere be cut by a plane P M P (*fig.* 35.), perpendicular to the line joining their centres, the depth of the electricity will be the same at all the points of the circle in which this plane intersects the spherical surface.

Fig. 35.



To determine the values corresponding to the distances selected in Coulomb's experiments, we have only to substitute these distances, viz. 30°, 60°, 90°, and 180° for φ in the values of A_n, and to make the necessary computations. Let the corresponding values of x be x', x'', x''', and x'''', and we find

$$\varphi'=30°,\quad \cos.\varphi'=\frac{\sqrt{3}}{2},\quad x'=0{\cdot}137\,.\,\frac{h}{r};$$

$$\varphi''=60°,\quad \cos.\varphi''=\frac{1}{2},\quad x''=0{\cdot}599\,.\,\frac{h}{r};$$

$$\varphi'''=90°,\quad \cos.\varphi'''=0,\quad x'''=0{\cdot}803\,.\,\frac{h}{r};$$

$$\varphi''''=180°,\quad \cos.\varphi''''=-1,\quad x''''=0{\cdot}916\,.\,\frac{h}{r}.$$

At these four points Coulomb found that the angles of torsion representing the proportional depths were in the ratio of the following numbers:

$$A'=0{\cdot}166$$
$$A''=0{\cdot}640$$
$$A'''=0{\cdot}800$$
$$A''''=0{\cdot}846$$

Taking the depth of the electricity at 90° from the point of contact to be expressed by 800, the several depths observed and computed are placed in juxtaposition in the following table, and the ratios of the observed to the computed values are expressed in the fourth column.

Distances from point of contact.	Depth of Electricity.		Ratio of observed to computed Depth.
	By Theory.	By Observation.	
30°	137	166	1·21
60°	599	640	1·07
90°	803	800	0·91
180°	916	846	0·92
Mean ratio of the observed to the computed values - - - - - -			1·025

Thus theory in this case comes within a 40th part of the results of observation. Coulomb brought two spheres, whose diameters were in the ratio of 1 to 2, into contact, and having electrified them observed, with the proof plane and the electrometer, the depth of electricity on each of them, at points whose distances were 60°, 90°, and 180°, from the point of contact. To compare the results of theory with those experiments in this case, we shall now investigate the formulæ applicable to it.

PROPOSITION VII.

(177.) *Two conducting spheres, the diameter of one of which is double that of the other, are brought into contact and charged with electricity: it is required to determine the distribution of the fluid on each of them.*

I. On the smaller.

In this case $r = 2r'$, and $m = \frac{2}{3}$. Let φ preserve its signification, and let

$$B_n = \frac{4(n+1)}{\{(n+2)^2 - 2(n+2)n \cos. \varphi + n^2\}^{\frac{3}{2}}}$$

Then, by Poisson's formula, we shall have

$$x_1 = \frac{2h}{r'}\{B_0 - B_1 + B_2 - B_3 + \ldots .\}$$

II. On the greater.

In this case $m = \frac{1}{3}$; and if x_2 be the thickness, we shall have

$$x_2 = \frac{h}{r}\{A_0 - A_1 + A_2 - A_3 + \ldots .\}$$

where A_n retains its former signification.

(178.) Two such spheres were submitted to experiment by Coulomb, who observed the proportional depths of the fluid on the smaller sphere, and found that throughout a range of 30° round the point of contact the depth was insensible. He found that at 60°, 90°, and 180°, the proportion of the depths was represented by the following numbers: —

60° - - 339
90° - - 577
180° - - 770.

If the values of x_1 corresponding to these values of φ be computed from the preceding formula, we shall find them to be as follows: —

$$60^\circ \;-\; -\; 0{\cdot}321\;.\;\frac{h}{r'}$$

$$90^\circ \;-\; -\; 0{\cdot}577\;.\;\frac{h}{r'}$$

$$180^\circ \;-\; -\; 0{\cdot}781\;.\;\frac{h}{r'}.$$

These results are placed in juxtaposition in the following table, and compared as before.

Distance from point of contact.	Depth of Electricity.		Ratio of the observed to the computed Depth.
	By Theory.	By Observation.	
60° 90° 180°	321 577 781	339 577 770	1·06 1·00 0·99
Mean ratio of the observed to the computed value - - - - - -			1·02

The result of theory, therefore, comes within a 50th part of the mean result of observation.

(179.) Coulomb compared the depth on the two spheres at 90° from the point of contact, and found the depth on the lesser to exceed the depth on the greater in the ratio of 125 to 100.

If the value of x_2 corresponding to $\phi=90°$ be computed from the preceding formula, we shall find it to be $0·928\,\frac{h}{r}=0·464\,\frac{h}{r}$. Hence the ratio of this depth to the depth at the corresponding points on the smaller sphere is that of 0·464 to 0·577, or 124 to 100, very nearly. The accordance of theory with observation is here also perfect.

PROPOSITION VIII.

(180.) *Two conducting spheres, whose diameters are in the ratio of one to four, are brought into contact and charged with electricity: to determine the distribution of the fluid on the smaller sphere.*

Preserving the signification of the symbols, let

$$C_n=\frac{8(n+2)}{\{(n+4)^2-2n(n+4)\cos.\varphi+n^2\}};$$

and if x_1 be the depth corresponding to φ, we shall have

$$x_1=\frac{4h}{r}\{C_0-C_1+C_2-C_3+\ldots.\}$$

Coulomb submitted such spheres to experiment, and observed the relative depths of the electricity on the smaller sphere corresponding to $\phi=90°$ and $\phi=180°$, and found the ratio of the latter to the former to be that of 143 to 100.

If these values be substituted for ϕ in the above expression, and the computations be made, we shall find the corresponding values of x_1 to be for $\phi=90°$ $x_1=0·349\,.\,\frac{h}{r}$, and for $\phi=180°$ $x_1=0·584\,.\,\frac{h}{a}$. The ratio of the latter to the former is that of 167 to 100 nearly.

(181.) It appears from all the cases, therefore, in which electrified spheres have been observed in actual contact, that the electrical state in which they are actually found to be is exactly the state in which the theory of two fluids would enable us to predict that they should be. When they are separated and removed from the influence of each other, their electrical state is found also to be in exact accordance with this theory.

It now remains to examine and to compare observation, so far as it has been carried, with theory, in the cases in which two spheres without being in contact are nevertheless placed so near each other that the electricity upon each of them shall exercise such an influence on the electricity upon the other as to cause it to change its manner of distribution over the surface, rendering its depth at various parts of the surface different from what it would be if each sphere were uninfluenced by the position of the other. We shall limit ourselves here to particular cases in which the mathematical results are least complex, and which may be verified most easily by observation.

Proposition IX.

(182.) *Two conducting spheres of given diameters are placed at a given distance from each other, and charged with given quantities of electricity: it is required to determine the manner in which the fluid will be distributed on each of them by means of their mutual influence.*

Let the symbols in the former propositions retain their signification, and let the distance between their centres be a, and let the radius of the smaller sphere r' be inconsiderable compared with $a-r$. The angle φ is understood to be measured from the line joining the centres. Also let D and D′ be the mean densities of the fluids on the spheres respectively. The whole quantities with which the spheres are charged and their magnitudes being known, the depths D and D′ must be known.

By Poisson's formula we shall then have

$$x_1 = D + D' \cdot \frac{r'^2}{ar} - D' \cdot \frac{r'^2(a^2-r^2)}{a^2 r\{a^2 - 2ar \cos. \varphi + r^2\}^{\frac{3}{2}}};$$

$$x_2 = D' - 3D \cdot \frac{r^2}{a^2} \cos. \varphi' + \frac{5}{2}(1 - 3\cos.^2\varphi') \cdot \frac{r^2 r'}{a^3} \cdot D;$$

where ϕ refers to the sphere whose radius is r, and ϕ' to that whose radius is r'.

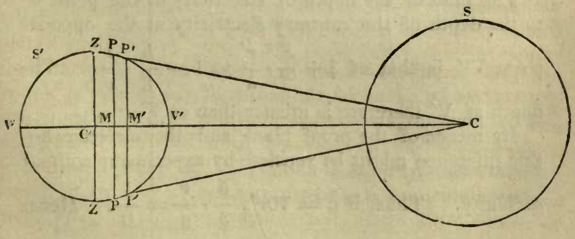
It is necessary to observe, that D and D′ are to be taken with a positive or negative sign, according as the electricity with which the spheres are respectively charged is positive or negative. Also the values of ϕ or ϕ' which render x or x' positive correspond to those parts of the spheres where the electricity is positive, and those which render x or x' negative correspond to points where the electricity is negative.

(183.) To investigate the particular case in which the lesser sphere in its natural state is placed at the distance a, under the influence of the greater sphere charged with electricity, it is only necessary to suppose $D'=0$ in the above formula for x_2. This gives

$$x_2 = -3D \cdot \frac{r^2}{a^2} \cos. \varphi' + \frac{5}{2}(1 - 3\cos.^2\varphi')\frac{r^2 r'}{a^3} D.$$

Let S and S′ (*fig.* 36.) be the two spheres.

Fig. 36.



To determine the state of the sphere S′ at the point V′, where the line CC′ joining the centres meets the surface, let $\phi'=0$, and we find

$$x_2=-3\mathrm{D}\,.\,\frac{r^2}{a^2}\left(1+\frac{5}{3}\frac{r'}{a}\right).$$

If the electricity of the sphere S be positive, this value of x^2 is negative; and if the former be negative, this value is positive. Hence the electricity at V′ is of a different kind from that with which the sphere S is charged.

(184.) To determine the state of the sphere S′ at the point V″ most distant from the sphere S, let $\phi'=180°$; $\therefore$ $\cos\phi=-1$. Hence

$$x_2=3\mathrm{D}\frac{r^2}{a^2}\left(1-\frac{5}{3}\cdot\frac{r'}{a}\right).$$

Since we have proceeded on the supposition that r' is inconsiderable in magnitude compared with $a-r$, it is still more so compared with a. Hence $\frac{r'}{a}$ must be less than $\frac{3}{5}$, and therefore $1>\frac{5}{3}\frac{r'}{a}$. Hence this value of x_2 must have the same sign as D, and therefore the electricity at the point V″ is of the same kind as that with which the sphere S is charged. It is consequently of a different kind from the electricity at the point V′.

The ratio of the depth of electricity at the point V′ to the depth of the contrary electricity at the opposite point V″ is that of $1+\frac{5}{3}\cdot\frac{r'}{a}$ to $1-\frac{5}{3}\cdot\frac{r'}{a}$. The depth at V′ therefore is greater than at V″.

By means of the proof plane and the electrometer, this inference might be verified by experiment without difficulty. Thus, if $a=10r'$, $\frac{5}{3}\cdot\frac{r'}{a}=\frac{1}{6}$. Hence the depth at V′ will, in this case, be to the depth at V″ as $1+\frac{1}{6}$ is to $1-\frac{1}{6}$, or as 7 to 5. In general, however, when $\frac{r'}{a}$ is very small, these depths are nearly equal.

(185.) Since the electricities at the opposite points V′ and V″ are of different kinds, it is evident that some intermediate part of the sphere S′ must be in its natural state. To determine at what distance from V′ this takes place, it is only necessary to find the value of ϕ', which renders $x_2=0$. Thus we have the condition

$$3 \cos. \varphi' + \frac{5}{2}(1-3\cos.^2\varphi') \cdot \frac{r'}{a} = 0.$$

This equation will in general give two values of $\cos. \phi'$, but it will be found that one of them is < -1, and would therefore correspond to an imaginary value of ϕ'. The other only is admissible. This value is

$$\text{Cos.}\, \varphi' = \frac{a}{5r'}\left(\sqrt{1+\frac{25r'^2}{3a^2}}-1\right)$$

If $\left(1+\frac{25r'^2}{3a^2}\right)^{\frac{1}{2}}$ be developed in a series, and the terms involving the third and higher powers of $\frac{r'}{a}$ be neglected, we shall find

$$\text{Cos.}\, \varphi' = \frac{5}{6} \cdot \frac{r'}{a}.$$

A circle on the surface of the sphere S′, at the distance thus determined from the point V′, passes through all the points of the sphere which are in their natural state.

This circle can be easily found by geometrical construction. The distance of its plane from the centre C′ will be $r' \cos. \phi'$. But

$$r' \cos. \varphi' = \frac{5}{6} \cdot \frac{r'^2}{a}.$$

From the centre C of the sphere S let a tangent C P′ (*fig.* 36.) be drawn to the sphere S′, and from the point of contact P′ let a perpendicular P′M′ be drawn to the line C′ V′. The distance $C'M' = \frac{r'^2}{a}$; and therefore if C′M be taken equal to five sixths of C′M′, and M P be drawn perpendicular to C C′, the circle P P will be that which corresponds to the points of the surface of the sphere which are in their natural state.

(186.) By the common principles of analysis, it appears that all values of cos. ϕ' greater than that which renders $x^2 = 0$ will render it > 0, and all less values will render it < 0. Hence it is easily inferred that on all parts of the surface of the spherical segment, whose base is the neutral circle P P, and whose vertex is V′, the electricity is of a different kind from that with which the sphere S is charged, and on all parts of the surface of the spherical segment having the same base, and whose vertex is V″, the electricity is of the same kind as that with which the sphere S is charged.

It can also be inferred that the depth of the electricity continually increases from the neutral circle to the points V′ and V″, at each of which it is a *maximum*.

As the sphere S′ is gradually removed from S, the point of contact P′ of the tangent continually approaches the point Z, which is the extremity of the diameter perpendicular to C C′; and since the neutral circle P always lies between P′ and Z, this circle must approach to the great circle of the sphere perpendicular to the line C C′ as the distance of S′ from S is increased. It appears, therefore, that when a small sphere, such as a pith ball, is placed under the influence of an electrified sphere, but at a distance from it many times greater than the radius of the small sphere, then that hemisphere of the small sphere which is turned towards the electrified sphere will be charged with electricity different from that of the electrified sphere, and the other hemisphere will be oppositely electrified.

We shall now examine a case of the mutual influence of two electrified spheres, to which we have formerly referred, and which was presented in the experimental researches of Coulomb.

PROPOSITION X.

(187.) *Two unequal spheres in contact are electrified, and then separated: it is required to determine the distribution of electricity on them, when placed under the influence of each other at a distance.*

In order to avoid very complex mathematical formulæ, we must here limit the question to the case in which $\frac{r'}{r}$ is a small fraction; that is, to the case in which the two spheres are very unequal in magnitude.

It appears by what was proved in (168.) that under these circumstances

$$\frac{D'}{D}=\frac{\pi^2}{6}.$$

But by Proposition IX. we have

$$x_2=D'-3D\,.\frac{r^2}{a^2}\cos.\varphi'+\frac{5}{2}(1-3\cos.{}^2\varphi').\frac{r^2r'}{a^3}\,.\,D$$

Omitting the terms of which $\frac{r'}{a}$ is a multiplier, and eliminating D′, we obtain

$$x_2=D\left(\frac{\pi^2}{6}-3\cos.\varphi'\,.\,\frac{r^2}{a^2}\right).$$

To determine the state of S′ at the point V′, let $\cos.\varphi'=1$, and we have

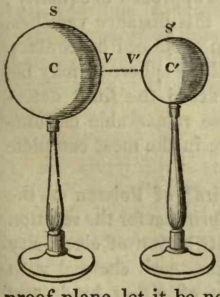
$$x=D\left(\frac{\pi^2}{6}-3\frac{r^2}{a^2}\right).$$

This will have the same sign with D if $\frac{\pi^2}{6} > 3\frac{r^2}{a^2}$, or $\frac{\pi}{3\sqrt{2}} > \frac{r}{a}$. It will be $=0$ if $\frac{\pi}{3\sqrt{2}} = \frac{a}{r}$, and will have a sign contrary to that of D if $\frac{\pi}{3\sqrt{2}} < \frac{r}{a}$. But $\frac{\pi}{3\sqrt{2}} = \frac{3}{4}$ very nearly. Hence we infer that the electricity at V′ is similar to or different from that with which S is charged, according as the distance of the centre C′ of the lesser sphere from the surface of the greater is greater or less than one third of the radius of the greater; and that if its distance from that surface be equal to one third of the radius of the greater, then the point V′ will be in its natural state.

(188.) Let us briefly recapitulate these remarkable consequences. If a small sphere (S′) be placed in contact with a great electrified sphere (S), the electricity at the point of contact (V′) will be nothing, that point being in its natural state. When they are separated (that point (V′) being still kept in the line of centres), the point V′ will be electrified by an electricity contrary to that of the sphere S. This electrified state of the point V′ will first gradually increase, and having attained a maximum, then gradually decrease in intensity as the sphere S′ is moved from the sphere S, until the distance of the centre (C′) of the smaller sphere from the surface of the greater sphere becomes equal to one third of the radius of the greater sphere (very nearly), and at that distance the point V′ will return to its natural state. If the smaller sphere be moved to a greater distance from the greater sphere, the point V′ will be electrified with electricity similar to that with which the greater sphere is charged.

(189.) To simplify the formulæ, we here suppose the radius of the lesser sphere to be so small that terms of which $\frac{r'}{r}$ is a multiplier may be neglected; but if the spheres be unequal, whatever be the proportion of their radii, a series of phenomena similar to that explained above will be produced, and the formulæ given by Poisson will always be sufficient to determine by calculation the distance at which the point V′ of the lesser sphere is reduced to its natural state. These results of theory have been confirmed by experiment, but it is desirable that such experiments should be multiplied and varied. Such experiments may be made by providing several spheres with metallic surfaces, mounted on glass pillars, and attended with all the usual precautions, to secure perfect insulation, and to preclude, as far as possible, all error arising from the effect of atmospheric dissipation; the experiments should be made in cold and dry weather, when the air holds but little vapour in suspension. The supports should be so regulated that the centres C C′ (*fig.* 37.) should be at the same height. After having brought two such spheres into contact, and electrified them, they should be separated to a very small distance. The proof plane should be then applied at V, the point of contact on the greater sphere. On testing it by an electroscope, it will be found to indicate electricity of the same kind as that with which the spheres were charged. After having discharged the electricity of the proof plane, let it be next applied to the point V′ on the lesser sphere. On testing it in the same manner, it will be found to indicate electricity of a different kind from that of the greater sphere. Let the sphere S′ be moved a little further from S, and let the same process be repeated, and the same results will be obtained; and this

Fig. 37.



will continue until S′ is removed to a certain distance, at which the point V′ will be found in its natural state.

(190.) Before these results of theory were discovered, Coulomb obtained, in several of his experiments, a series of phenomena similar to the preceding. In one of his experiments, the globe S was eleven inches and S′ was eight inches in diameter. So long as the distance V V′ was less than an inch, the electricity at V′ was contrary to that of the globe S. When the distance was equal to an inch, the sphere S′ at V′ was in its natural state, and beyond this distance the electricity at V′ was similar to that of the globe S.

When a globe, S′, of four inches in diameter was brought into contact with one of eleven inches, the point V′ was not reduced to its natural state until the distance V V′ was two inches; and when the smaller globe was two inches diameter, this state was produced at the distance of two and one third inches.

It appears from these experiments that the distance V V′, at which all signs of electricity disappear at the point V′, diminishes as the spheres approach to equality; and when they are actually equal this distance vanishes, the neutral state of V′ being then produced by contact. On the other hand, however small the sphere S′ may be, this distance, V V′, never can exceed the limit determined in Prop. X. In all these remarkable circumstances, theory and observation are in the most complete accordance.

(191.) In the beautiful Memoirs* of Poisson on the theory of electricity, he has given formulæ for the solution of the general problem of the distribution of electricity on the surfaces of any two spheres, each charged with any given quantity of electricity of either kind, and placed under the influence of each other at any given distance. In the great generality of this problem he has far outstripped the limits to which experimental research has yet attained, and has placed the theory in a condition to supply the experimental inquirer with information as to a variety of circumstances affecting the electrical state of bodies, which will serve to guide his proceedings in the course which will lead most surely to the extension of knowledge in this part of physics.

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* The mathematical student will be well rewarded for the labour of studying these fine pieces of mathematical physics, and the experimental electrician who may not be able to comprehend their details will be at least directed by their results to the best course of experiment. — See *Mémoires de l'Institut*, 1811.

It appears by these formulæ that the phenomena evolved by the mutual influence of two electrified spheres will have an important dependence of the relation between the quantities of electricity with which they are charged, and the quantities with which they would be charged if they were brought into contact.

(192.) Let a certain quantity of electricity, which we shall call Z, be shared between two spheres, so that E being the portion given to one, E′ will be the portion given to the other. We shall then have

$$Z = E + E'.$$

Now if the spheres, being charged with the total quan tity of electricity expressed by Z, be brought into con tact, the fluid will distribute itself between them in a certain proportion determined by the ratio of their radii. Let the portion which each would receive under these circumstances be e and e'. We shall therefore have, also,

$$Z = e + e'.$$

If the quantities E and E′ are different from e and e' (which generally happens when the spheres are electrified without contact), and the spheres be placed as in *fig.* 37., and moved towards each other, the depth of electricity at the points V and V′ must undergo a continual increase as the distance V V′ is diminished. Now, since the pressure of the electricity at any point of a conductor against the air which confines it upon that surface increases as the square of the depth, this continual augmentation of pressure will at length enable the fluid to overcome the resistance of the air at V or V′; and when it does so it will escape, and will pass from the one surface to the other; and such an effect will usually be accompanied by a visible spark, and such a noise as is produced by the impact of one hard substance against another. The state of the points V and V′ before the spark is oppositely electrical, the one being positive and the other negative. If the electricities E and E′ are of the same kind—positive, for example—and if E be greater than E′, then, as the spheres approach to contact, the electricity at V′ will become negative, while the electricity at V will continue positive, and will increase in depth. But if E and E′ are of opposite kinds, then the electricities of the points V and V′, as they approach, will be of the same kind as that of the electricities with which the spheres respectively are charged.

In the case in which E and E′ are of the same kind, E being greater than *e*, and E′ less than *e*′, the influence of the E upon E′ is to repel it towards the more remote parts of the sphere S′, and at the same time E by its attraction and repulsion decomposes a portion of the natural electricities of the sphere S′, drawing towards the point V′ that part of the decomposed electricity which is of a contrary kind from itself, and driving the electricity of the same kind towards the opposite side.

When the spark is produced and contact takes place, the distribution of the electricity Z between the spheres is suddenly changed, and the quantities with which the spheres are respectively charged become *e* and *e*′.

These phenomena would not be produced if the condition

$$\frac{E}{E'}=\frac{e}{e'}$$

were observed by the electricities E and E′; that is to say, if the electricities were imparted to the spheres in the same proportion as they would be if electrified in contact. This easily appears from the mathematical formulæ. For the first term in the expression of the value of the depth of the electricity at V and V′ has the form

$$\frac{2(\mathrm{D}d'-\mathrm{D}'d)}{\{a-(r+r')\}\mathrm{Y}};$$

where D and D′ are the mean depths of E and E′, and *d* and *d′* the mean depths of *e* and *e′*, and Y is a quantity which involves log. $\{a-(r+r')\}$. Now if the condition

$$\frac{\mathrm{D}}{\mathrm{D}'}=\frac{d}{d'}$$

be not fulfilled, the numerator of the above expression will be finite. Hence as a is diminished, and approaches to equality with $(r+r')$, $a-(r+r')$ will be diminished; and since $\{a-(r+r')\}$ log. $\{a-(r+r')\}$ becomes $=0$ when $a-(r+r')$ becomes $=0$, it follows that the above quantity must become infinite when the spheres come into contact; and consequently before that takes place, the atmospheric pressure must be overcome, and the interchange of electricity take place, which is usually attained by the spark and explosion.

But if the condition

$$\frac{\mathrm{D}}{\mathrm{D}'}=\frac{d}{d'}$$

be observed, then the numerator of the above will be $=0$ and the value of the depth at V and V′ will be $=0$, and no discharge will take place, since no electricity will pass from either sphere to the other.

(193.) Among the various consequences of the theoretical investigations of Poisson, one is entitled to more particular notice, as it suggests an experiment which affords a striking verification of the theory. He has shown that a relation may be adopted between the radii of the two spheres and the quantities of electricity with which they are charged, so that there shall be certain distance of the centre of the lesser sphere S′ from that of the greater S, at which the electricity shall be distributed uniformly over the lesser sphere, exactly as it would be if that sphere were removed altogether from the influence of the greater. This state, however, is not owing to the sphere S exercising no action on S′, but from a peculiar condition of equilibrium arising from the reciprocal action of the two spheres.

(194.) The difficulty which is presented in reducing this and other results of the theory to the test of experiment, is that which attends the process of giving to the two spheres charges of electricity which have any required ratio to each other. This may, however, be effected by the following method.

The two spheres are first placed in contact, and electrified. Being separated, the electricity will be distributed between them in the ratio e to e', which is due to contact, and which is known by theory. This, however, may be confirmed by the proof plane and the electrometer. Let the ratio of the required charges be $\frac{\mathrm{E}}{\mathrm{E}'}$, and let us suppose that $\frac{e}{e'} > \frac{\mathrm{E}}{\mathrm{E}'}$. In that case it will be necessary to deprive the sphere S of a part of its electricity, to reduce the ratio of the charges to $\frac{\mathrm{E}}{\mathrm{E}'}$. Now, let $\frac{\mathrm{E}}{\mathrm{E}'}=\mathrm{M}$, $\frac{e}{e'}=m$, and let $\mathrm{E}'=e'$.

$$\text{Hence } \mathrm{E}-e=(\mathrm{M}-m)\mathrm{E}'=\frac{\mathrm{M}-m}{\mathrm{M}}\,.\,\mathrm{E}.$$

Hence it appears that of the whole charge E a fractional part is to be removed, expressed by $\frac{\mathrm{M}-m}{\mathrm{M}}$; and as M and m are both given, the question is reduced to the discovery of a method of abstracting from the electrical charge of a sphere a given part.

Now, it has been shown (101.) that if a circular disc of metal be brought into contact with a sphere charged with electricity, the fluid will distribute itself between the sphere and disc in proportion to the magnitude of their surfaces. If, therefore, the magnitude of the disc be a certain fractional part of the magnitude of the spherical surface, the disc by contact will receive a proportional part of the electricity with which the sphere is charged; and being removed from the sphere, the latter will be deprived of that proportion of its charge.

To apply this principle, let A be the total superficial magnitude of the disc, including both surfaces; and let S be that of the sphere. Then, if E be the charge of the sphere, the disc will receive the quantity $\frac{A}{A+S}.E$. We shall then have

$$\frac{M-m}{M}=\frac{A}{A+S}; \quad \therefore A=S.\frac{M-m}{m}.$$

By which the magnitude of the disc, which will take the necessary portion of electricity from the sphere, may be determined.

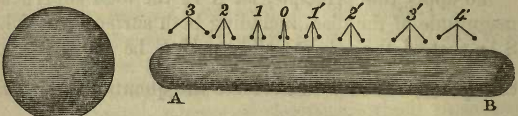
To reduce these expressions to terms involving only the radii of the disc and sphere, let $r=$ the radius of the sphere, and $R=$the radius of the disc. Hence we have

$$S=4r^2\pi, \quad A=2R^2\pi; \quad R^2=2r^2\frac{M-m}{m};$$

$$\therefore R=r\sqrt{\frac{2(M-m)}{m}}.$$

(195.) It appears, from the theoretical expressions obtained for the depth of electricity at various parts of two electrified spheres brought near each other, that these depths are, even when the spheres are nearest each other, materially different from what they are after contact. This difference is not confined to those parts of the spheres which are near the point of contact, but prevails throughout their entire surfaces. It follows, therefore, that at the moment of contact, or, more strictly, at the moment of the spark passing between them, a sudden change is produced in the depth of the electricity on every part of each of the spheres. This is equally true with respect to conductors of every form, and may be easily verified by experiment. For this purpose let a conductor, such as is represented in *fig.* 38., having several pairs of pith balls placed upon

Fig. 38.



it, suspended by linen thread, be electrified. The divergence of the balls will be greater or less, according to the depth of electricity, at the parts where they are suspended. If a metallic sphere be brought into contact with this conductor, and a spark passes between them, all the pith balls will undergo a sudden change, each pair changing instantaneously their angle of divergence.

CHAP. VIII.

ELECTRICAL ATTRACTIONS AND REPULSIONS EXPLAINED.

(196.) Having explained the theory by which the phenomena of electricity have been brought under the dominion of mathematics, and by which the effects of bodies electrified under given circumstances may be predicted, it now only remains to complete this branch of our subject by showing how, by the agency of the two electric fluids, the movements which are imparted to electrified bodies brought near each other can be accounted for.

It appears, in the first place, to be satisfactorily established by direct experiment, that the electric fluids exert no force of attraction or repulsion on the material particles of the bodies upon which those fluids are diffused. The immediate escape of electricity from conductors, when relieved from the atmospheric pressure, is a sufficient evidence of this with regard to that class of bodies; and although its departure from nonconductors under like circumstances is not quite so rapid, there is nothing in the phenomena to indicate the existence of any attraction general or specific between the molecules of electricity and the particles composing these bodies, the nonconducting quality being simply one by which the *superficial* movement of the electric fluid on the body is prevented or very much obstructed. Whether, then, we consider the one class of bodies or the other, the conductors or the nonconductors, the atmosphere must be regarded as a *coating of nonconducting matter,* under and within which is confined the shell of electric fluid by which the body is invested. The *form* and *thickness* of that shell are determined by the forces exerted by the molecules of electricity on each other, and on the natural electricities of the body, as well as by the forces exercised on them by the electricity of other bodies in the neighbourhood; but the *shell itself* is held together by the atmosphere alone. In fact, the surrounding atmosphere confines this shell of electric fluid exactly as gas is confined within a bladder.

(197.) Let us first, then, consider the case of the attraction or repulsion which is apparently exerted by an electrified body, S, on a *nonconducting* body, S′, also electrified.

In this case the electric fluid on S attracts or repels the electric fluid on S′, each molecule of the one fluid acting separately on each molecule of the other, according to the laws already assigned. Now, since the pressure of the surrounding air prevents any motion of the fluid in a direction perpendicular to the surface of S′, and the nonconducting power forbids any superficial motion of the particles of fluid, no change of position *inter se* can ensue, and the shell of electric fluid will preserve its form exactly as if it were solid matter encrusting the body S′. The attraction or repulsion of the fluid on S must therefore cause a motion of the entire shell of fluid on S′ to or from the body S; and as this preservation of the form of the electric shell necessarily requires the continuance of the body which it invests within it, that body must accompany it as it moves to or from the body S.

(198.) This may be illustrated in the following manner. Let us suppose a sphere of cork to have its surface covered by iron dust, and imagine this dust to be pressed against the surface of the cork by a surrounding atmosphere whose pressure is sufficient to prevent its escape from the surface. Also suppose that the roughness of the surface of the cork is sufficient to prevent the particles of iron from moving upon it. Let this sphere be placed near a powerful magnet. The iron will be strongly attracted, and, if free, would leave the cork and fly to the magnet. But this is prevented by the causes just stated. The iron can neither leave the cork nor shift its position upon it. It must therefore move towards the magnet in virtue of the attraction exerted on it, carrying the sphere of cork which it invests along with it.

(199.) If the body S′ attracted or repelled be a conductor, the circumstances are somewhat different. In that case, the electric fluid upon it has a freedom of superficial motion more or less perfect in proportion to the conducting power of the body. There is, however, a certain distribution which it will assume, and in which it will maintain itself, depending on the form of the body S′, and on the influence exerted by the electricity of S. So long as the position of S and S′ remain unchanged, the electric fluid on S′, thus distributed, is stationary. Let us suppose that while S′ is fixed in any given position it were suddenly to be deprived of its conducting power, and to become a nonconductor, and left at liberty to move. Then S′ would move towards or from S, as we have already shown that an electrified nonconductor would do. Let it be supposed that this motion is allowed to take place through a very small space, which we shall call dx; and after having moved through this space, suppose the conducting power of S′ to be restored, and the body again to be fixed. The influence of the electricity of S on that of S′ will now be a little different in consequence of the small change, dx, which has taken place in the distance between them. On the restoration of the conducting power, the electricity of S′ will undergo a change in its distribution on the surface of that body, and it will assume that distribution which corresponds to the new relative position which the two bodies have assumed.

When the electric fluid on S′ has come to rest after this change, let S′ be supposed a second time to be deprived of its conducting power, and to be at liberty again to move. As before, it will move, as a nonconductor would do, to or from S. After it has moved through a small space, dx, let it be stopped as before, and let its conducting power be restored. Another change in the distribution of electricity will now take place, and the fluid will take a new position of equilibrium on S′, conformably to the change which has taken place in the relative position of the two bodies. If, in like manner, the conducting power be once more annihilated, and the body S′ liberated, another small motion, dx, will take place, and so on.

Now, let it be supposed that this succession of changes shall proceed without any intermission, and that the spaces dx, which divide the intervals at which the electrical state of S′ undergoes a sudden change, are infinitely small. In fact, suppose the change of the distribution of electricity on S′ not to be *intermitting* but *continuous*, and the progress of S towards or from S′ not to be made by a succession of movements broken by intervals of rest, but to be made by one continued motion, then the same reasoning would hold good, and the actual effects which take place when an electrified conductor is placed near another electrified body would ensue.

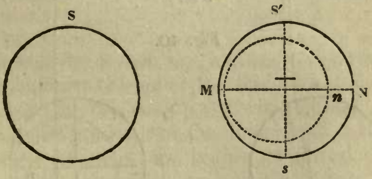
(200.) In this illustration we have regarded only the effects produced on one of the two electrified bodies, considering the other as fixed; but the same reasoning will be evidently applicable to the other, and the reciprocal attractions and repulsions thus become matter of easy explanation. When the bodies thus mutually acted upon are conductors, it is not only the distribution of the electricity with which they are originally charged that undergoes a continuous change with their continuous change of mutual position, but there is a constant development of natural electricity, by which their electrical condition is affected. This, however, does not in any way interfere with the reasoning by which we have here accounted for the reciprocal movements by which such bodies are affected.

One of the two bodies, as S′, may be originally in its natural state, and it nevertheless will exhibit the effects of an attraction exerted upon it by an electrified body, S, in its neighbourhood. In this case, a decomposition of its natural electricities takes place before any motion is produced, and a shell of free electricity is formed at its surface, a part of which is of one kind, and a part of the other. This shell, being acted upon by the electricity of S, the effect of the attraction on the *nearer* portion of electricity (of a contrary kind to that with which S is charged) is greater than the repulsion exerted on the electricity of the same kind which is on the side of S′ most remote from S. The whole effect is, therefore, an attraction on the shell, by which it is drawn towards S, and with it, according to the reasoning already explained, the body S′, enveloped by this shell of electricity, is carried.

Such appears, according to my views, to be the manner in which the apparent attractions and repulsions of electrified bodies may be accounted for, on the principles of the theory of two fluids. As this, however, is not the manner in which these effects are usually explained, and as the question may be important, involving, as it does, the application of the theory to the most familiar effects of electricity, we shall here briefly state the method of accounting for these phenomena, proposed by M. Biot, and adopted and quoted by most other elementary writers on this part of physics.

Let S′ (*fig.* 39.) be a sphere of conducting matter

Fig. 39.

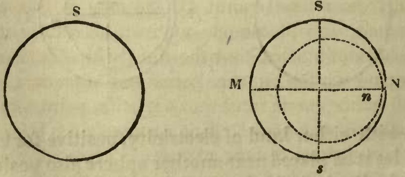


charged with either kind of electricity, positive for example, and let it be placed near another sphere also positively electrified. By the influence of the electricity of the sphere

S, the electricity of S′ will not be distributed uniformly on it, as would otherwise be the case, but will accumulate in greater quantity on the side most remote from S. In fact, the inferior surface of the electric fluid on S′ may, in a general sense, be imagined to be represented by the dotted circle. It is proved by theoretical principles that the electricity confined upon a body by the surrounding air presses against the air with a force which is proportional to the square of the depth of the electric fluid. In the present case, the depth of the fluid on the hemisphere S′ N *s* is greater than on the hemisphere S′ M *s*; and if the sum of the squares of the depths at every point of the one be compared with the sum of the squares of the depths at every point of the other, the excess of the sum on the hemisphere S′ N *s* would be much greater than on the hemisphere S′ M *s*. The electric fluid on S′ N *s*, therefore, presses against the atmosphere in the direction N with greater force than that with which the fluid on S′ M *s* presses in the contrary direction; and therefore the fluid and the body invested by it must move in the direction of the greater pressure; that is, must recede from the body S, which is similarly electrified. Hence an apparent repulsion will take place.

If the sphere S′ be negatively electrified, the fluid upon it will accumulate in greater quantity on the side S′ M *s*, and its inferior surface will be represented by the dotted circle in *fig.* 40. In this case, for the

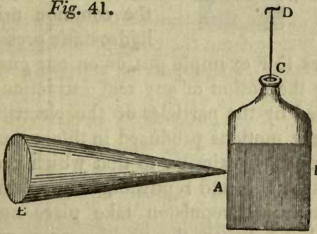
Fig. 40.



reasons explained above, the fluid on the hemisphere S′M *s* will press against the air with greater force than the fluid on the hemisphere S′N*s*, and a movement of the sphere S′ in the direction N M will ensue. Hence an apparent attraction of the sphere S electrified positively will be exerted on the sphere S′ electrified negatively.

Such is the ordinary method of explaining these effects, and the following illustration of it is given by M. Biot: — "Although the proposition which declares that similarly electrified bodies attract, and oppositely electrified bodies repel each other," says M. Biot, "appears to be a mere statement of the phenomena, we must beware not to attach to these terms (attraction and repulsion) any notion of absolute reality, since motions of the same kind may be produced without any real attraction or repulsion existing between the particles of the two bodies. As an example of this, let us imagine a glass vessel A B (*fig.* 41.) filled with a heavy

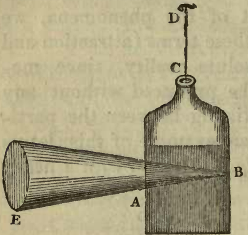
Fig. 41.



fluid, such as water or mercury, and suspended vertically by a cord from a fixed point D. So long as this vessel is untouched, it will remain at rest, according to the common laws of statics, and the fluid which it contains will suffer no motion in the horizontal direction, since it presses with equal force on opposite points of the inner surface of the vessel. But suppose that, by means of a burning glass, a cone of rays is directed upon a point A. in the side of the vessel, and a hole is made by melting the glass. The fluid will issue from this hole, and the pressure at A, in the direction B A, will be removed; while the pressure at the point B, corresponding to A on the other side of the vessel, will continue. The vessel and its contents will accordingly yield to the excess of pressure in the direction A B, and will deviate from the vertical position, in the same manner as if it were *repelled* by the lens E.

"If, on the other hand, the cone of rays be directed on the point B, as represented in *fig.* 42., and the hole be made there, the contrary effect will be produced, and the vessel with its contents will deviate from the vertical in the direction B A, as if it were *attracted* by the lens. Nevertheless, there is not in either case any true attraction or repulsion, and the effects only arise from the common principles of hydrostatic pressure. Now, not only does this example put us on our guard against entertaining the notion of any real attraction or repulsion exercised by the particles of the electrified body; but these very motions produced in this example result from a mechanism similar to that which produces the apparent attractions and repulsions of electrified bodies. The attraction and repulsion take place not between the bodies, but between the positive or negative fluids which envelop them, and of which the mutual action causes the pressure to be increased on some parts of their surfaces, and diminished on others; which pressure is exerted against the surrounding air, by which the fluids are retained on the bodies, or in general against whatever obstacles are opposed to its displacement."

Fig. 42.



(201.) The explanation founded on these principles has always appeared to me to be inconclusive and unsatisfactory, and the illustration by which it is accompanied to be inapplicable. The motion of the sphere S′ is here not ascribed *directly* to the attraction or repulsion of the electricity of S acting on the electricity of S′. It is ascribed to the *unequal diffusion* of the electricity on S′, which unequal diffusion is produced by the proximity of S. But if the unequal diffusion of the fluid on S′ by producing an excess of pressure on the one side against the air above that on the other is really the cause of the motion of S′, then that motion would ensue by any other cause which, *without the proximity of another electrified body,* would produce such unequal distribution of the fluid. But such would not be the case; for if a *nonconducting* sphere, a sphere of gum lac for example, be strongly electrified on one side, and either feebly or not at all electrified on the other, then such sphere ought, according to the preceding explanation of the phenomena, to move spontaneously towards that side on which it is most strongly electrified. It is scarcely necessary to observe that no such motion would take place.

But, independently of this practical instance of the inconclusiveness of this explanation, it is evident that by a general principle of mechanics no motion can be imparted to the centre of gravity of any system by the reciprocal actions of the parts, or any of them, composing that system; and whenever such a motion takes place, it must be due to the action of some cause external to and separate from the system. In the preceding explanation, nevertheless, it is assumed that by the mutual repulsions of the unequally distributed fluid, and by those alone, a motion of translation is given to the whole body S′.

In fact, whatever be the pressure which the electric fluid at any part of an electrified body exerts against the air, an equal pressure in the contrary direction must be exerted on the body itself by the inferior surface of the electric fluid. This is a necessary consequence of the perfect fluidity of that fluid. Thus, in *fig.* 40., if the fluid presses against the air at N with a certain force, there must be an *equal pressure* exerted against the matter of the sphere at *n*, and *in the contrary direction.* These two pressures are then in equilibrium; and the same may be said of the pressure exerted by the electricity at any other point. However unequal, therefore, may be the pressures exerted by the electricity against the air, these pressures will be balanced by equal and contrary pressures exerted against the sphere S′ itself, and no motion could consequently ensue.

The illustration of the vessel of liquid having a hole in its side, from which a stream of the liquid issues, is quite inapplicable. That example is altogether analogous to the cases of motion produced in electrified bodies by the rapid escape of electricity *at points*, examples of which have been given in (117.) *et seq.* But in the present case no escape of the fluid from the electrified body takes place, and therefore the motion of *recoil* or *reaction* cannot ensue.

In fine, it appears that the motion of an electrified body *from* a body similarly electrified, and *towards* a body oppositely electrified, is due *not* to the *unequal distribution* of the electric fluid upon it, which in this respect must be considered as a merely accidental circumstance, but to the mutual attraction or repulsion of the masses of electric fluid on the two bodies.

(201.) In the reciprocal motion exhibited by electrified bodies, some cases occur which, at the first view, would appear to be contrary to those which might be inferred from theory; but, as happens with all hypotheses having a foundation in truth, such apparently exceptional cases, when they come to be strictly examined, serve only as further verifications of the theory.

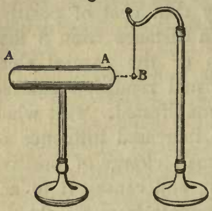
When two electrified bodies, one of which is very small compared with the other, but feebly electrified, approach each other, effects ensue contrary to what are usually produced. Suppose that S, the greater, is strongly charged with positive electricity, and S′ is feebly electrified and also positively. At a certain distance S′ is, as usual, repelled. But if it be gradually brought nearer to S, the repulsion is by degrees diminished, and it is at a certain distance *attracted*. This attraction continues to increase until contact takes place, after which S′ is repelled, as bodies in the natural state usually are after contact with an electrified body.

These effects are easily accounted for. The body S′, being first invested with a very thin coat of positive electricity, and placed at such a distance from S that an inconsiderable decomposition of the natural electricities of S is produced, the usual repulsion exerted on the shell of electric fluid is manifested. But when the distance is diminished, the increased influence of the electricity of S repels the small charge of positive electricity previously given to S′, and causes it to accumulate at the side of S′ most remote from S. At the same time, the influence of S′ decomposes a portion of the natural electricities of S′, causing the negative portion to accumulate at the side of S′ nearest to S, and the positive at the side most remote from it, where it is added to the charge of positive fluid collected there. There will be thus an accumulation of positive fluid on the side of S′ most remote from S, which we shall call P, and of negative fluid on the nearest side, which we shall call N. Now, the *quantity* of P is greater than that of N, and on that account the repulsion exercised by the electricity of S on P would be greater than its attraction on N. But, on the other hand, the distance of P being greater than the distance of N from S, the repulsion on that account exerted on P would be less than the attraction exerted on N. When the distance of S′ from S is so small that the excess of the attraction above the repulsion due to the *difference of distance* is greater than the excess of the repulsion above the attraction due to *difference of quantity*, the body S′ will be attracted, and will, *à fortiori*, be attracted at all less distances.

When contact takes place, S′ receives from S a charge of positive electricity so great that the excess of attraction and repulsion due to difference of distance is insufficient to neutralise the contrary excess due to difference of quantity, and repulsion will take place at all distances.

(202.) These effects may be verified experimentally in the following manner. Let A A′ (*fig.* 43.) be an insulated conductor, and let B be a pith ball suspended near it by a thread of silk, and attached to the conductor by another horizontal thread, A B, by which it shall be prevented from receding further from the conductor. Let A A′ be first feebly electrified: the ball B will be attracted, will touch the conductor, and will then be repelled as far as the thread A B will permit. Let the conductor now receive a stronger charge: the ball B will be again attracted, and again repelled, and this may be continued until the ball B becomes so strongly charged with electricity that it can be no longer repelled.

Fig. 43.



CHAP. IX.

ELECTRICAL MACHINES.

(203.) In the commencement of this work, the structure and the forms of the machines by which the electric fluid is developed and accumulated for the purposes of experiment, and the details of some of the principal instruments by which the presence of that fluid is ascertained, its quality detected, and its quantity measured, were explained, so far as was necessary to render intelligible the development of the electrical phenomena, and the theory founded upon them, which are the subject-matter of the preceding chapters. A full and accurate explanation of the principle and structure of electrical machines, and other apparatus commonly used either in imparting a knowledge of the science, so far as it is known, or in experimental investigations made with an immediate view to extend its limits, required a previous acquaintance with those facts and principles which have now, it is hoped, been explained with sufficient clearness and precision. We shall, therefore, proceed with the description of the form, structure, and operation of electrical machines, and such other experimental apparatus as admit of being explained on those general principles of the science which have been already established, reserving for a subsequent part of this work such other instruments and apparatus as rest upon principles and facts to be developed hereafter.

All machines, whatever be their form, for the evolution and accumulation of free electricity, must consist of three principal parts; — firstly, the rubber; secondly, the substance on which electricity is disengaged by friction; and, thirdly, the conductor on which the free electricity thus evolved is collected and accumulated for the purposes of experiment.

In all ordinary electrical machines, the rubber is a cushion stuffed with hair, bearing upon its surface some substance which, by friction with the second body above mentioned, will freely and abundantly evolve electricity. The substance against which the friction of this rubber takes place is invariably glass, that having been found in all respects most convenient and eligible for the purpose; and the form given to it is one which will admit of every part being brought in rapid and uninterrupted succession under the action of the rubber. The form best adapted for this purpose is either that of a cylinder revolving on its geometrical axis, the cushion being pressed against its side, or a flat circular plate of sufficient thickness to give it the requisite strength kept revolving in its own plane on an axis at right angles to that plane passing through its centre, the cushion being pressed against its faces. Electrical machines are accordingly divided into two classes, *cylindrical machines* and *plate machines.*

The conductor is a body having a metallic surface, and supported on insulating pillars, or suspended by insulating cords.

The Common Cylindrical Machine.

(204.) A hollow cylinder of glass, A B (*fig.* 44.), is supported in bearings at C, the extremities of its geometrical axis, on which it is capable of receiving a motion of continued rotation. In order to impart by a moderate velocity of the hand a sufficiently rapid motion to the cylinder, a small grooved wheel is attached to the end of the cylinder C, which is driven by a much larger grooved wheel, D, the two wheels being connected by a band in the usual manner, as represented in the figure. The bearings in which the cylinder turns are formed in upright pieces of wood, E F, attached to a rectangular base, E G, of sufficient magnitude and solidity to give the necessary firmness and stability to the apparatus. The cushion is represented at H, formed of soft leather stuffed with hair, and supported on a glass pillar. This cushion is more clearly represented in *fig.* 45. Between the cushion and the wooden back which supports it is interposed a steel spring, by means of which the face of the cushion is urged with the necessary pressure against the cylinder. By the elasticity of this spring the rubber accommodates itself to the inequalities of the cylinder. The foot of the glass pillar supporting the rubber is inserted in a groove formed in the base or table of the machine, in which groove the pillar carrying the rubber with it may, within certain small limits, be varied in its distance from the cylinder. It is fixed in any desired position by the adjusting screw I. A screw having a large spherical head, K (*fig.* 44. and *fig.* 45.), passes through the wooden back of the rubber. By means of this screw the tension of the spring behind the rubber is adjusted. This screw and its metallic knob, being conductors, form a free communication with the electricity evolved upon the rubber; and by suspending a metallic chain, K L, from the knob K, a communication may be made at pleasure between the rubber and

Fig. 44.

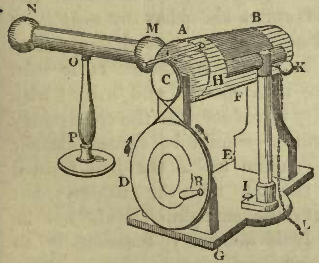
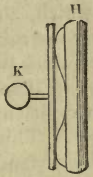


Fig. 45.



the ground, or with any other conductor. When the chain K L is removed, the rubber is insulated by the glass pillar on which it stands, and whatever electricity may be evolved upon it will be retained there. Attached to the superior edge of the cushion is a flap of silk, usually varnished, which extends over the cylinder, and terminates within about an inch of the place where the prime conductor is presented to it.

(205.) Although by the friction of a leather or silk cushion against the glass electricity would be evolved, its production would not be so rapid or abundant as other expedients, the effects of which depend on principles which will be explained hereafter, render it. It is found that the evolution of the electric fluid is stimulated by smearing the face of the cushion by certain amalgams of metals, which in this case, therefore, become the real rubber. An amalgam consisting of mercury and tin, in the proportion of two parts of the former to one of the latter, with the addition of a little chalk, was used by Canton. Singer proposed a compound of two parts by weight of zinc and one of tin, with which, in a fluid state, six parts by weight of mercury are mixed. The whole is then shaken in an iron or thick wooden box until it cools. It is then reduced to fine powder in a mortar, and mixed with lard in sufficient quantity to reduce it to the consistency of paste. This preparation should be spread cleanly over the surface of the cushion up to the line formed by the junction of the silk flap with the cushion ; but care should be taken that the amalgam should not be extended to the flap. It is necessary, occasionally, to wipe the cushion, flap, and cylinder, to cleanse them from the dust which the electricity evolved upon the cylinder always attracts in a greater or lesser quantity. It is found that, from this cause, a very rapid accumulation of dirt takes place on the cylinder, which appears in black spots and lines upon its surface. As this obstructs the action of the machine, it should be constantly removed, which may be done by applying to the cylinder as it revolves a rag wetted with spirits of wine. The production of electricity is greatly promoted by applying with the hand to the cylinder a piece of soft leather, five or six inches square, covered with amalgam. This is, in fact, equivalent to giving a temporary enlargement to the cushion.

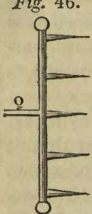
The purpose of the flap of silk coated with a varnish of gum is to protect the electricity evolved by the rubber on the glass from the contact of the air, by which it would be more or less dissipated. The gum varnish of the silk possessing in a very high degree the nonconducting quality, the electricity does not pass from the glass to it; and the flap covering the surface of the cylinder nearly to the points where it is in communication with the prime conductor, the electricity is protected until it passes to the latter.

The quality of glass best adapted for the cylinders has not been certainly ascertained; it is evident that it should be rendered as little hygrometrical as possible; which condition will be attained by rendering its composition as free from alkaline matter as is practicable. The use of minium in a greater quantity than is necessary should also be avoided, since it injures the insulating power of the glass. Cylinders are generally made of flint glass, and as thin as is consistent with the necessary strength. They should be free from knots and veins, and should be as true in their cylindrical form as practicable, that the pressure of the cushion may be uniform.

The practice of coating the inner surface of the cylinder with a resinous cement or varnish is now generally discontinued. It may, however, contribute to the improved action of a bad cylinder. The process consists in melting together four parts of Venice turpentine, one part of resin, and one of bees' wax, and boiling the whole together for about two hours in an earthen pipkin on a slow fire. The cylinder is to be carefully heated, and a portion of the liquid cement poured in. Then, by causing the cylinder to revolve while the cement is fluid, the latter will gradually harden, and form a permanent coating on the inner surface.

(206.) The prime conductor, M N, is a cylinder made of thin brass, the extremities being segments of a sphere of greater radius than the cylinder, and greater than hemispheres. This cylinder is supported on a strong glass pillar, O P, resting on a wooden stand of sufficient magnitude to give stability to the conductor. To the end of the conductor which is presented to the cylinder is attached a row of points, the bar from which these points project terminating in two varnished wooden balls. This appendage to the conductor is represented separately in *fig.* 46. A hole is made in the end of the conductor, in which the rod Q may be inserted, so that the points may be attached to it or removed at pleasure. When the conductor is properly placed, these points should stand within about half an inch of the surface of the cylinder.

Fig. 46.



(207.) The bearings on which the cylinder rests at each end are fastened into brass caps, which close two large orifices, one at each end of the cylinder. By means of these openings, the inner surface of the glass is made perfectly clean and dry before the cylinder is mounted; and a sufficient bed of some resinous cement is melted into each cap on the inside, so that no communications can take place between the external air and the air within the cylinder.

Since the electric fluid is evolved only on that part of the cylinder to which the rubber is applied, the glass beyond the ends of the rubber is covered with a varnish of gum lac, to prevent more effectually the electricity under the flap from passing along the cylinder and escaping by the metallic caps at its extremities.

As the object of the row of points is to act on, or be acted on, by the electricity on the cylinder, in a manner which will be presently explained, their extent should be equal to, and should not exceed, that of the cushion and the flap.

(208.) The efficiency of electrical machines must mainly depend on each of their several points discharging the functions assigned to them with the highest practicable degree of perfection; and among these functions, none is more important than perfect insulation. Now glass, which for many reasons sufficiently obvious is the most convenient substance which can be used as an insulator, offers a peculiar facility to the condensation of moisture upon its surface, and the moment such a film of water is formed upon it, its insulating virtue ceases. To remove or diminish the liability to this injurious effect, it is usual to cover the insulating pillar, and a portion of the cylinder, with a coating of some resinous varnish, which, while its nonconducting power is even greater than that of glass, offers less attraction to the moisture suspended in the air. A varnish for this purpose may be made by dissolving common sealing-wax in alcohol; but it is better, if possible, to apply the wax directly, by heating the surface which is to be coated by it. A varnish of gum lac is still better, that substance being a more perfect insulator than sealing-wax, and equally repellant of moisture.

(209.) With all the precautions which can be used, and with the very best experimental apparatus, electrical experiments will be very sensibly affected by the hygrometrical state of the air. They should be always performed in a warm and dry room, and every part of the apparatus intended to be used should be kept for some hours at a moderate distance before a fire, in order that all moisture deposited on them may be dissipated. This precaution must be understood as applying not only to electrical machines of every form, but also to all electrical apparatus whatever in which the property of insulation is required.

(210.) In fixing the insulating pillars or handles into their sockets, a cement is required which admits of being easily softened by heat. One of the best for this purpose is composed of five pounds of resin melted with one pound of bees' wax, one pound of red ochre, and two table-spoonfuls of plaster of Paris. The two last substances should be well dried, and gradually mixed with the wax and resin while in a state of fusion.

(211.) The only essential condition to be fulfilled by the *material* of the prime conductor is, that its external surface should be metallic; and the only essential condition to be fulfilled by its *form* is, that it should be such as not to permit the spontaneous dispersion of electricity. It has been shown that the free electricity of a conductor may be *practically* considered as superficial; for although, strictly speaking, it penetrates to a depth generally variable below its surface, yet that depth being incomparably more minute than the thinnest metallic foil with which any body can be coated, a conductor of a given form and magnitude of solid metal cannot contain more free electricity than one of the same superficial extent and form, however thin it may be. A globe of solid gold cannot contain more free electricity than a globe of equal magnitude formed of gilt paper.

For the sake, therefore, of lightness, metallic conductors are usually hollow. If they be cylindrical, which they generally are, their extremities are formed of segments of a sphere, not less than a hemisphere, to avoid corners or edges, which would facilitate the spontaneous dispersion of electricity. They are generally formed of thin copper or brass, which have the advantage of cheapness, are little liable to injury, and have surfaces easily polished.

Conductors formed of wood or pasteboard, coated with tin foil, or gold leaf, are sometimes convenient, and, if kept clean and in good order, answer very well. Whatever be the matter or form of the prime conductor, small round holes should be made in it at convenient places having a diameter of about the eighth of an inch into which the stems of electroscopes and other apparatus may be occasionally inserted.

(212.) To explain the operation of the electrical machine above described, let us suppose the handle R, *fig.* 44., turned, so as to make the wheel D revolve in the direction of the arrows. The wheel C and the cylinder will therefore turn in the opposite direction, so that the glass, after moving in contact with the cushion, and having positive electricity developed upon it, passes under the flap, and afterwards comes opposite the points projecting from the conductor. Negative electricity is at the same time developed in the cushion, and passes by the metallic screw and knob K and the chain K L to the ground. The positive electricity accumulated on the surface of the cylinder acts by induction on the natural electricities of the conductor NM; and according to what was explained in Chapter VI. the positive electricity of the conductor is driven towards the extremity N, while the negative electricity is attracted and accumulated round the extremity M. In this state of things let us suppose for a moment the conductor not to be armed with the system of points already described, but to be terminated by a spherical surface. The attraction of the positive electricity of the glass would, according to the principles already explained, accumulate negative electricity on the spherical surface at M, and this negative electricity would re-act on the positive electricity of the glass, and would have a tendency to collect it in increased quantity at the part nearest the conductor; but this tendency would be resisted by the nonconducting quality of the glass, on which the stratum of free electricity would maintain a depth, little, if at all, augmented. Under such circumstances no electricity could pass either from the cylinder to the conductor, or from the conductor to the cylinder, unless the depth of the electric fluid on the one or the other surface were so great as to overcome by its force the pressure of the surrounding air. Now it is clear that the nonconducting property of the glass conspires with its cylindrical form to prevent this on the one hand, while the facility to accumulation offered by the conducting power of the spherical surface M is counteracted by the property of that surface in virtue of which it favours the uniform distribution of electricity on the other. That the conductor may become charged with free electricity, either of two effects must be produced. The depth of electricity on the cylinder must be so increased as to overcome the restraining power of the air, so that it may force its way to the spherical surface M, and thus the conductor may become charged with the positive electricity which passes to it from the cylinder; or the depth of the negative fluid on the surface M must be so increased as to surpass the restraining power of the air, so that a portion of the negative fluid shall pass from the conductor to the cylinder. In this latter case the quantity of positive fluid remaining on the conductor would exceed the quantity of negative fluid, and if the conductor were removed from the cylinder it would be found charged with positive electricity. The negative fluid, which would in this case pass from the extremity M of the conductor to the cylinder, would there combine with an equal portion of the positive fluid diffused upon the cylinder, and would, to a proportionate extent, restore the cylinder to its natural state. If the quantity of negative fluid thus supplied by the conductor to the cylinder were exactly equal to the quantity of negative fluid which escaped through the rubber and the chain K L to the earth, then it would necessarily be equal to the quantity of positive fluid developed on the cylinder, and the cylinder would be obviously restored to its natural state. The electricities which would thus be combined as the cylinder passes before the conductor would be again decomposed as it passes under the rubber, and the negative fluid which was just received from the conductor would be dismissed through the rubber and the chain K L to the earth.

Now it is evident that, consistently with the principles of this theory, either of these two methods of charging the conductor with positive electricity may be adopted. Either a positive charge of electricity may be supplied from the cylinder to the conductor, or a quantity of negative electricity may be drawn from the conductor to the cylinder, and dismissed through the rubber to the earth, leaving an equal portion of free and uncombined positive electricity on the conductor.

But there are practical circumstances which decide the choice between these two methods. To produce such an increased depth of fluid as would overcome the resistance of the air, the adoption of an angular or pointed form would be necessary, and this would be incompatible with the continued action of the cylinder; but, independently of this, supposing that points could be attached to the cylinder to facilitate the escape of electricity from it, the nonconducting power of the cylinder would obstruct the flow of the electric fluid towards these points, and would therefore render the expedient inefficacious.

Neither of these difficulties, however, attends the adoption of the other method. The conductor, being stationary, may have a system of points or any other appendages easily attached to it; and when the points are thus attached to it, the perfect freedom of motion of the electric fluid upon it enables it to collect at the points with the depth which the general condition of electrical equilibrium requires; and as the depth greatly exceeds what would give a force equal to that of the atmosphere, a rapid escape of electricity will take place.

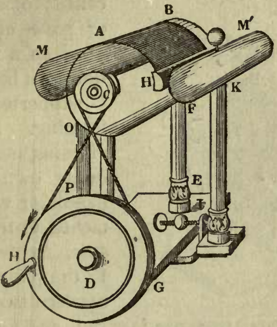
After these explanations, there can be little difficulty in perceiving the process which is effected by the operation of this electrical machine. By the friction of the amalgam on the cushion with the glass, the natural electricities of one or both of these substances are decomposed. The negative electricity escapes by the chain to the earth; and the positive electricity remaining upon the glass, over a width of the cylinder determined by the length of the cushion, is carried by the motion of the cylinder under the flap towards the end of the conductor. Coming opposite the conductor, its attraction draws the negative portion of the natural electricity of the conductor towards M, and drives the positive portion towards N. The negative portion accumulates in great depth at the row of points which are close to that part of the cylinder electrified positively. This great accumulation at the points is favoured partly by the property of points formerly explained (115.), and partly by the proximity of the point to the attracting fluid. The negative fluid, therefore, issues in copious jets from the several points, and, diffusing itself on the cylinder, combines with and neutralises the positive fluid; and accordingly the lower part of the cylinder between the point and the rubber is always in its natural state.

(213.) It is apparent, therefore, that the effect produced by the operation of this machine is a continued decomposition of the natural electricities of the prime conductor, and an abstraction of the negative fluid. This process would continue until the quantity of positive fluid disengaged upon the conductor would become so great that the repulsive force of the positive fluid on the cylinder would be insufficient to expel it from the extremity of the conductor next the cylinder, where its presence would be incompatible with the accumulation of the negative fluid, and, consequently, all transmission of negative electricity from the conductor to the cylinder would cease, and no further accumulation of positive electricity on the conductor would take place.

Nairne's Cylindrical Machine.

(214.) The electrical machine represented in *fig.* 47. was constructed by Mr. Nairne with a view to the development of either positive or negative electricity. The chief parts of this machine are so similar to those of the last, that it will not be necessary to give any detailed description of them. The corresponding parts are marked in the two figures by the same letters. The conductor M is in this case placed with its length parallel

Fig. 47.

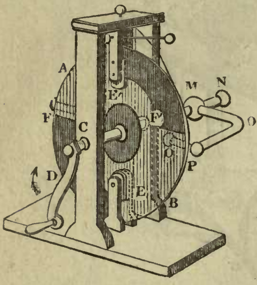


to the cylinder; and the points project from its side, and not from its end as in the former case. The negative conductor M′ supports the rubber, and receives from it the negative electricity; not by induction, as is the case with the positive conductor, but by communication. If it be required to accumulate positive electricity, a chain must be carried from the negative conductor to the ground, otherwise an inconsiderable quantity only of positive electricity could be collected on the conductor M. If, on the other hand, negative electricity be required, then the conductor M must be put in communication with the ground, and the conductor M′ insulated. By this arrangement the repulsion of the positive electricity on the cylinder will constantly drive a portion of the positive element of the natural electricities of the conductor M to the earth, and its attraction will act with undiminished effect on the negative element collected about the points. The accumulation of negative electricity on the conductor M′ will continue until its repulsive power becomes so great as to stop the further decomposition of electricity by the cushion.

The Common Plate Machine.

(215.) This machine is represented in *fig.* 48., and consists of a circular disc or plate of glass, A B, fixed in a vertical position on a horizontal axis, C, supported in a wooden framing. It is capable of being made to revolve in its own plane by a handle or winch, D, attached to the end of its axis. At the lowest part, E, the plate is embraced between two cushions, to which a regulated pressure is given, and a casing of silk covers both faces of the plate from the cushion to a point, F, within about an inch of the horizontal diameter. The cushions and cover together, therefore, extend over something less than a quadrant, and the breadth of the silk cover is equal to the length of the cushion.

Fig. 48.



The plate is embraced in a similar manner at its highest point by two similar cushions, E′, and covered by a similar casing of silk extending to F′, a point a little above the opposite end of the horizontal diameter. The handle being turned in the direction of the arrow, vitreous electricity will be developed upon the glass by the friction of each of the cushions. The conductor is composed of a long narrow cylinder, bent at angles so as to bring it into the proper position with respect to the plate, and formed at its angles into spheres to avoid edges or corners. It is represented at N M, which is in the direction of the axis of the plate. A branch, M O, is thence carried parallel to the plate, which, being bent at right angles, is terminated in a sphere at P, close to the plate. A short branch, P Q, is thence carried parallel to the plate contiguous to the edge of the silk flap. A similar bent branch of the conductor extends on the other side, terminating just above the edge of the lower flap.

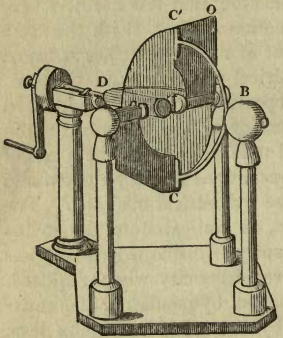
The principle of this machine is so similar to that of the common cylindrical machine, that it is needless here to offer any further explanation of it. With the same weight and bulk, the extent of rubbing surface is much greater than in the cylindrical machine, and the evolution of electricity is proportionably more rapid. In the construction and adaptation of the rubbers, and in the general adaptation and management of the parts of the machine, the same precautions are to be taken and provisions made as in the cylindrical machine. The principal objection to this, as compared to the cylindrical machine, is the difficulty of insulating the rubbers so as to obtain the negative electricity when required. This end is sometimes attained by insulating the entire apparatus, which is done by mounting it on glass legs. The object is, however, much more elegantly and effectually attained in the machine which we shall now describe.

The Haerlem Plate Machine.

(216.) By far the most splendid and powerful electrical machine which has been constructed is that which was made under the superintendence of Doctor Van Marum for the Teylerian Museum of Haerlem. As it may be considered one of the most perfect models for such a piece of apparatus, we shall here give a detailed account of it.

A view of this machine is given in *fig.* 49. The cushions are each insulated on a pillar of glass, and are applied at opposite ends of the horizontal diameter of the plate. Silk covers are attached to them, as already described in the common plate machine. A metallic sphere, B, supported on a glass pillar, is the prime conductor; and to it is attached a rod of metal bent into a semicircular form, the diameter of the semicircle corresponding to that of the plate, and the plane of the semicircle being perpendicular to the plate. At the extremities of this semicircular piece are two small cylinders, C and C′, presented with their sides to the plate, and having their sides armed with points presented to the surface of the glass. The effect produced by these metallic points upon the positive electricity diffused upon the glass as it leaves the flap is exactly the same as in the case of the common cylindrical machine.

Fig. 49.



(217.) Since it is necessary that the cushions should each communicate with the ground when the conductor B is to be charged with positive electricity, there is another semicircular branch, similar to C B C′, attached to the axis of the plate at D, but placed in a horizontal position, so that its extremities shall be in contact with the cushions respectively; and as this semicircular piece is in metallic communication with the ground, the negative electricity developed on the cushions escapes by it to the earth.

If it be required to charge the conductor B with negative electricity, the semicircular piece C B C′ is moved from the vertical to the horizontal position, so that the cylinders C and C′ shall have their points presented to the cushions instead of the glass. A provision for this movement is made in the apparatus. The position of the other semicircular piece on the opposite side of the glass is in this case likewise changed, its extremities being presented to the glass at the top and bottom of the plate near the points where it moves from under the flaps charged with positive electricity.

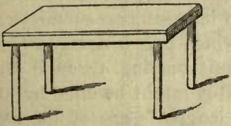
Whether the prime conductor be charged with positive or negative electricity, the effect is produced by a decomposition of its natural electricities, and the abstraction of the electricity contrary to that with which it is charged. This process has been so fully explained in the case of the common cylindrical machine, that it need not be repeated here.

(218.) Having explained the principal varieties of electrical machines, we shall now briefly notice some appendages to them which are necessary or useful in almost all experiments in which these machines are applied.

Appendages to Electrical Machines.

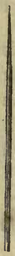
(219.) When it is required to preserve the electricity on a conductor, and to prevent its escape to the earth, it is usual to place it on a stool (*fig.* 50.) having glass legs coated with a varnish of gum lac. The top is usually made of a piece of mahogany or other strong and hard wood, which should be baked and subsequently varnished. The legs should be six or eight inches in length, and formed of solid cylinders of glass, from an inch to an inch and a half in diameter. They should be fixed into holes in the under side of the stool by proper cement.

Fig. 50.



As it is frequently necessary to examine the effects of points and spheres, pieces such as are represented in *figs.* 51, 52, should be provided, to be occasionally inserted in holes in the prime conductor; also metallic balls attached to rods having glass handles (*figs.* 53,54.), for cases in which it is desired to apply to an electrified body a conductor, without allowing the electricity to pass to the body of the person conducting the experiment.

Figs. 51. 52. 53. 54.

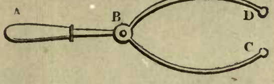


Pieces of brass chain to make occasional communications between one conductor and another; boxes of small balls about the size of medical pills made of the pith of rush or elder, silken threads, fine silver wires, fine linen threads steeped in salt and water, for the suspension of the balls, should be also provided.

(220.) It is frequently necessary to establish a temporary metallic communication between two conductors, so that the electricity with which one is charged may be shared by the other without passing through the body of the experimenter. This might be done by attaching a chain of sufficient length to one of the two conductors, and supporting the end of it by a glass rod held in the hand of the operator. It might thus be brought into contact with the other conductor. Under such circumstances, the electricity would pass between the two conductors through the chain. But as this process is one so constantly necessary, instruments called *dischargers* are constructed expressly for the purpose.

The jointed discharger is represented in *fig.* 55., where A B represents a glass handle, B D and B C brass wires terminated by metallic balls moving on a pivot or joint at B, by which they may be opened or closed at pleasure, so that the distance between D and C

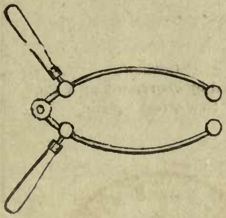
Fig. 55.



can be varied as may be required. Previously to the experiment, the opening of the legs is adjusted according to the distance between the bodies between which a metallic communication is to be made.

It is sometimes more convenient to be enabled to adjust the distance of the balls D and C in the performance of the experiment: for this purpose handles of glass are attached to the legs of the discharger, as represented in *fig.* 56.

Fig. 56.



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